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THE LABORATORY PERFORMANCE OF THE ANDEFT/SC-320 MODEM WITH AN HF MULTIPATH FADING CHANNEL SIMULATOR

G. C. Porter

July 1967

DIRECTOR OF AEROSPACE INSTRUMENTATION
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L G Hanscom Field, Bedford, Massachusetts

(Prepared under Contract No. AF 19(628)-67-C-0160 by General Dynamics, Electronics Division, Rochester, New York)

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FOREWORD

The results of the laboratory tests of the ANDEFT/SC-320 modem with the General Dynamics HF Multipath Fading Channel Simulator performed under Contract No. F19628-67-C-0160 are reported herein as an expansion of the data contained in the final report under Contract No. AF 19(628)-5536. The final report (ESD-TR-66-639) entitled "A Frequency-Differential Phase-Shift Keyed Digital Data Modem for Operation at 4800, 2400, 1200, and 600 Bits Per Second Over Long-Range HF Paths" describes the principles of operation of the modem and the results of back-to-back additive white Gaussian noise performance tests.

REVIEW AND APPROVAL

This technical report has been reviewed and is approved.

Clement V. Horrigan

for OTIS R. HILL, Colonel, USAF
Director of Aerospace Instrumentation
Program Office

ABSTRACT

A laboratory test program to evaluate the performance of the ANDEFT/SC-320 frequency-differential PSK HF modem operating with the General Dynamics HF Multipath Fading Channel Simulator is described. The modem was operated in six modes (4800 bps, 2400 bps/4-phase, and 2400 bps/2-phase; diversity and non-diversity) and performance was measured for simulated HF path conditions for four multipath delay spreads (0.5, 1, 2, and 5 ms), three fading bandwidths (0.2, 0.5, and 2.0 Hz), and three bit-energy-to-noise-density ratios (10, 20, and 40 db). The resulting data shows bit error rate performance at 4800 bps with diversity between 10^{-5} and 10^{-3} for multipath delay spreads between 0.5 and 2.0 ms, respectively, and a fading bandwidth of 0.2 Hz. Increasing multipath delay spread causes a much larger degradation in bit error rate than increasing fading bandwidth. Dual signal source reception diversity and dual inband frequency diversity are effective in producing improved bit error rates, especially at the smaller multipath delay spreads, i.e., 2 ms or less. Operation at 2400 bps/4-phase which includes both diversity techniques for 4-way diversity produced the best results. The multipath-limited error rate was so low for some channel parameters that it could not be established in 10^7 bits. For multipath-limited conditions, this mode out performed the 2400 bps/2-phase mode which does not include the inband diversity feature.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION I

INTRODUCTION

This report describes a series of laboratory tests performed to determine the bit error rate (BER) versus E_o/N_o* performance of the ANDEFT/SC-320 modem when operated with the General Dynamics HF Multipath Fading Channel Simulator. The results described were taken for three values of E_o/N_o (10 db, 20 db, and 40 db), four values of multipath delay dispersion (0.5 ms, 1.0 ms, 2.0 ms, and 5.0 ms), and three values of fading bandwidth (0.2 Hz, 0.5 Hz, and 2.0 Hz). For each set of fading bandwidth/multipath delay parameters, measurements of bit error rate were made for nondiversity and diversity reception for operation at 4800 bps with quadriphase modulation, 2400 bps with quadriphase modulation (this mode includes dual inband frequency diversity), and 2400 bps with biphase modulation. These modes are hereafter identified as 4800 bps, 2400 bps/4-phase, and 2400 bps/2-phase, respectively.

The test results encompass 216 data points which determine 72 curves (BER plotted as a function of E_o/N_o) and are presented in this report as 18 families using the four values of multipath delay dispersion as the parameter. Also included in this report is a brief description of the test methods and procedures and a short discussion of the results.

* E_o/N_o is defined as the ratio of energy per bit (including the energy in the synchronization tones) to the noise power in one (1) cycle of bandwidth.

SECTION II

THE MODEM

The ANDEFT/SC-320 is a variable rate (4800, 2400, 1200, or 600 bits per second) frequency-differential PSK digital data modem designed to operate in a 3 kHz bandwidth over long-range HF paths. The baseband spectrum consists of 66 tones including two first channel reference-sync tones which form 64 parallel, orthogonal, data channels, each of which carries 75 bits per second of data. The modem includes dual signal source diversity reception in all operating modes. Four-phase modulation is used (two bits of information are encoded on each tone) at 4800 bps and 2400 bps, and the latter mode includes dual inband frequency-diversity in addition to the reception diversity. (Channels separated by 1320 Hz carry the same information and are post-detection combined at the demodulator.) Two-phase modulation is used for the slower data rates, including a second 2400 bps mode which does not employ inband diversity. In this test series the performance of the modem is measured operating with an HF simulator at 4800 bps (one mode) and 2400 bps (two modes) with and without diversity reception. For complete detail on the frequency-differential technique as it is implemented in the ANDEFT/SC-320 refer to the final report.[1]

SECTION III

THE HF SIMULATOR

The General Dynamics HF Multipath Fading Channel Simulator is a laboratory test tool designed to provide representative fading multipath channel behavior for investigation and evaluation of communication system performance. It will reproduce many of the channel impairments commonly encountered by HF communications systems in operational environments.

Operating at baseband, the simulator, shown in block diagram form in Figure 1, is composed of two channels which share a common signal input and tapped delay line. Each channel consists of four randomly perturbed paths. The amplitude fading effects are provided by a set of "pseudo-random" cams which drive signal-modulating potentiometers. The cam profiles are linearly uncorrelated and have approximately Gaussian amplitude probability density characteristics. The fading bandwidth is adjustable by changing the speed of rotation and short term repetition of the fading pattern is avoided by driving the cams at slightly different speeds through an appropriately chosen set of chain and sprocket combinations.

The output of each channel is the linear sum of the four paths. Inputs for additive white noise are provided on a channel basis. Three outputs are provided: channel A, channel B, and the linear sum of both channels. The latter permits operation of the simulator as a single channel composed of eight fading paths.

Although the signal on each path is not subject to true Rayleigh fading (the amplitude probability distribution follows a Rayleigh law, but the phase distribution is not flat - the signal can assume only 0 or 180° phase shifts relative to the phase at the delay line tap), the output of the simulator does exhibit Rayleigh amplitude and phase statistics. This is accomplished by appropriate selection of tap points on the high resolution delay line (the number of taps on the delay line is much greater than the number of paths) such that the difference between any two taps is unique, and the smallest difference in delay is smaller than half the period of the highest frequency component of the input signal. Experimentally determined amplitude and phase probability distributions of this technique can be found in the references.[2,3]

In back-to-back white noise performance tests, bit error rate (BER) is measured as a function of the independently variable parameter, signal-to-noise ratio (E_o/N_o when expressed in terms of bit energy to noise density). The General Dynamics HF simulator provides two additional "path" parameters which are defined as fading bandwidth f_b and multipath delay spread T_d. The simulator is used with independent noise sources on each diversity reception line and these are varied to produce the desired signal-to-noise ratio. The fading bandwidth is varied over the range of 0.2 to 2.0 Hz by changing the speed of rotation of the cams which drive the signal-modulating linear pots. The delay spread or dispersion is varied over the range of 0.5 to 5.0 milliseconds by changing the path taps on the multi-tap delay line.

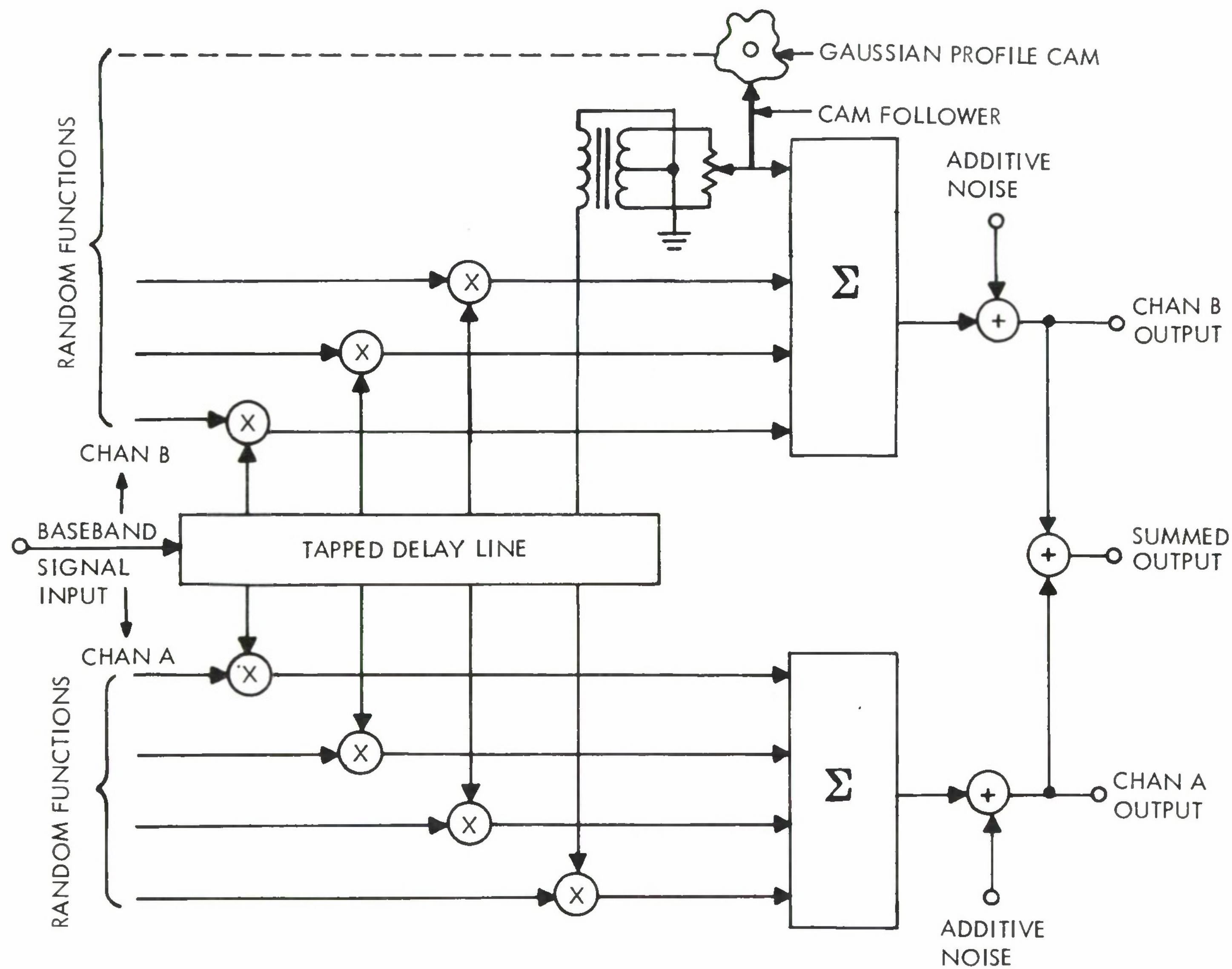


Figure 1. Block Diagram of HF Multipath Fading Channel Simulator

SECTION IV

TEST METHODS AND PROCEDURES

According to the test plan[4] prepared to set the methods and procedures for the laboratory tests, the equipment was operated as shown in the block diagram of Figure 2. A seven bit pattern (1110100) was generated by the pattern generator in the modulator and the composite modulator baseband signal was applied to the HF simulator. For diversity operation, the simulator was operated as shown in the diagram, and independent noise functions were added to each diversity line before application to the demodulator. After demodulation, the data was compared with the original transmitted pattern. Provision was made for counting errors and total received bits on laboratory decade counters. For nondiversity tests, the simulator was operated in its nondiversity mode, one noise source was used, and the demodulator was operated in the "line 1" position.

To facilitate the data taking, a data/run sequence and system of identification was devised and is shown in Figure 3. For each fading bandwidth, the operating modes, six in all, were setup in the order shown in the figure, top to bottom. For each operating mode the four multipath delay spreads were simulated and three signal-to-noise ratios set. Using a four digit number established according to the sequence shown in the right-hand column in Figure 3, the data was taken and identified starting with the first point (1111) for a fading bandwidth of 0.2 Hz through the last point (3643) for a fading bandwidth of 2.0 Hz. The data sheets in the Appendix are keyed in this manner.

The data run times were arbitrarily set to run 10^7, 5×10^6, and 2×10^6 bits at 4800 bps for fading bandwidths of 0.2, 0.5, and 2.0 Hz, respectively. For operation at 2400 bps, the same data run times were used so that 5×10^6, 2.5×10^6, and 1×10^6 bits were run, respectively, for the fading bandwidths above.

Simulator and modem control settings were defined by the test plan. Calibration for E_o/N_o was also performed according to an established procedure used earlier in the back-to-back tests. In order to provide for precisely 10 db, 20 db, and 40 db settings for E_o/N_o, the measured SNR in a 4250 Hz bandwidth was set 0.5 db higher than the indicated E_o/N_o for operation at 4800 bps and 2.5 db lower for operation at 2400 bps. Therefore, measured SNR was 10.5, 20.5, and 40.5 db for 4800 bps operation and 7.5, 17.5, and 37.5 db for 2400 bps operation.

Before starting the simulator performance tests, the back-to-back additive white Gaussian noise performance of the modem was verified by measuring bit error rate as a function of the noise power density for nondiversity operation at 4800 bps and 2400 bps (both 2-phase and 4-phase modes). This data is shown in Figure 4. By comparison with earlier data[5], it was verified that the back-to-back performance was equal to or better than the reference data.

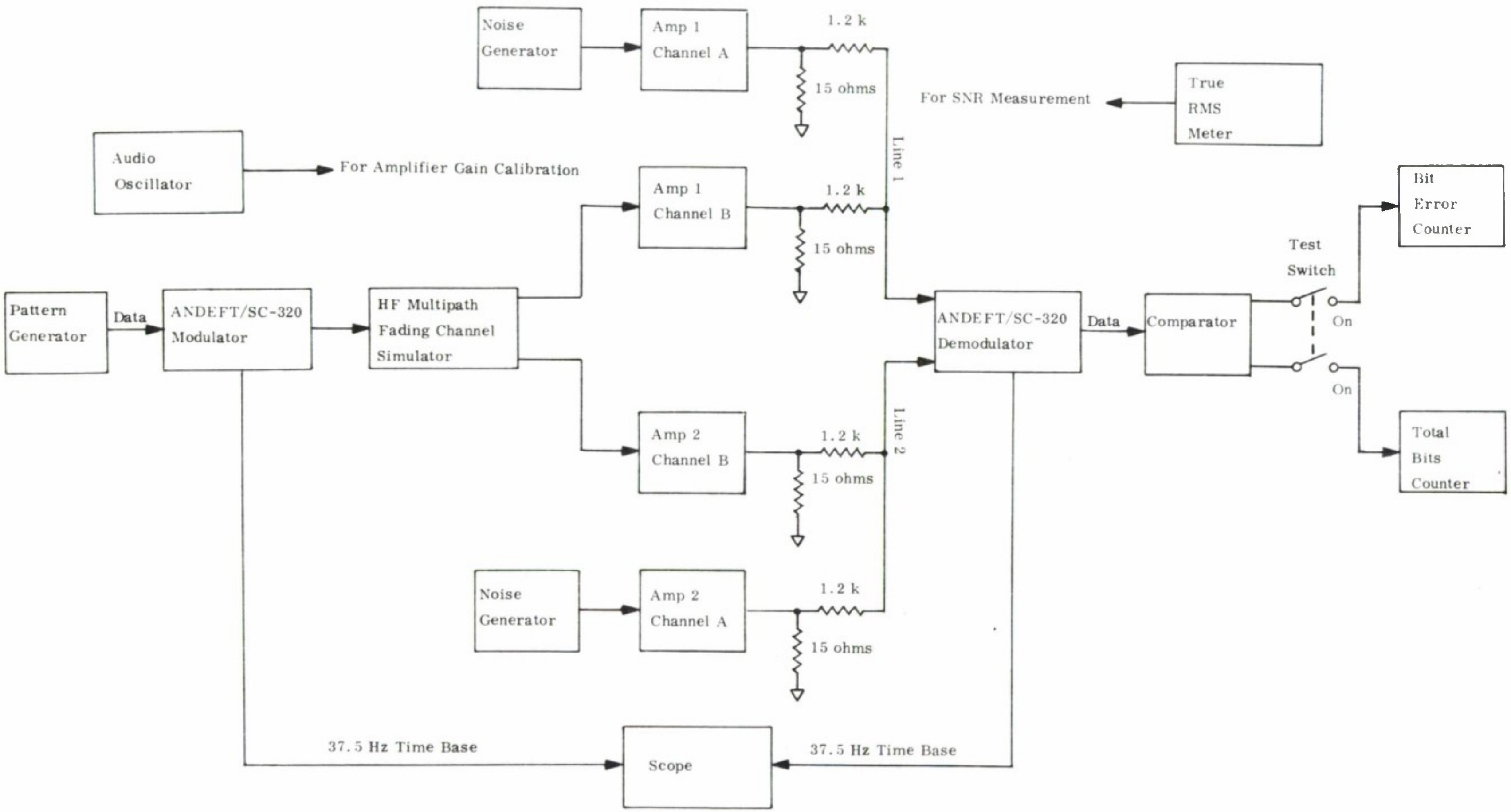


Figure 2. Block Diagram of ANDEFT/SC-320 Operating with HF Multipath Fading Channel Simulator

Fading Bandwidth f_b	Mode	Multipath Delay Spread T_d	E_o/N_o	Ident. No. *
f_b = 0.2 Hz	4800/4-phase/Diversity	T_d = 0.5 ms	10 db	(1111)
			20 db	(1112)
			40 db	(1113)
		T_d = 1.0 ms	10 db	(1121)
			20 db	(1122)
			40 db	(1123)
		T_d = 2.0 ms	10 db	(1131)
			20 db	(1132)
			40 db	(1133)
		T_d = 5.0 ms	10 db	(1141)
			20 db	(1142)
			40 db	(1143)
	4800/4-phase/Nondiversity	T_d = 0.5 ms	10 db	(1211)
			20 db	(1212)
			40 db	(1213)
		T_d = 1.0 ms	10 db	(1221)
			20 db	(1222)
			40 db	(1223)
		T_d = 2.0 ms	10 db	(1231)
			20 db	(1232)
			40 db	(1233)
		T_d = 5.0 ms	10 db	(1241)
			20 db	(1242)
			40 db	(1243)
	2400/4-phase/Diversity	T_d = 0.5 ms	10 db	(1311)
			20 db	(1312)
			40 db	(1313)
		T_d = 1.0 ms	10 db	(1321)
			20 db	(1322)
			40 db	(1323)
		T_d = 2.0 ms	10 db	(1331)
			20 db	(1332)
			40 db	(1333)
		T_d = 5.0 ms	10 db	(1341)
			20 db	(1342)
			40 db	(1343)
	2400/4-phase/Nondiversity	T_d = 0.5 ms	10 db	(1411)
			20 db	(1412)
			40 db	(1413)
		T_d = 1.0 ms	10 db	(1421)
			20 db	(1422)
			40 db	(1423)
		T_d = 2.0 ms	10 db	(1431)
			20 db	(1432)
			40 db	(1433)
		T_d = 5.0 ms	10 db	(1441)
			20 db	(1442)
			40 db	(1443)
	2400/2-phase/Diversity	T_d = 0.5 ms	10 db	(1511)
			20 db	(1512)
			40 db	(1513)
		T_d = 1.0 ms	10 db	(1521)
			20 db	(1522)
			40 db	(1523)
		T_d = 2.0 ms	10 db	(1531)
			20 db	(1532)
			40 db	(1533)
		T_d = 5.0 ms	10 db	(1541)
			20 db	(1542)
			40 db	(1543)
	2400/2-phase/Nondiversity	T_d = 0.5 ms	10 db	(1611)
			20 db	(1612)
			40 db	(1613)
		T_d = 1.0 ms	10 db	(1621)
			20 db	(1622)
			40 db	(1623)
		T_d = 2.0 ms	10 db	(1631)
			20 db	(1632)
			40 db	(1633)
		T_d = 5.0 ms	10 db	(1641)
			20 db	(1642)
			40 db	(1643)

*Ident. No. refers to data run/point as defined by parameters. Series 1111 thru 1643 is for f_b = 0.2 Hz; series 2111 thru 2643 is for f_b = 0.5 Hz; series 3111 thru 3643 is for f_b = 2.0 Hz. See also, text and data sheets.

Figure 3. Data Run/Point Sequence and Identification

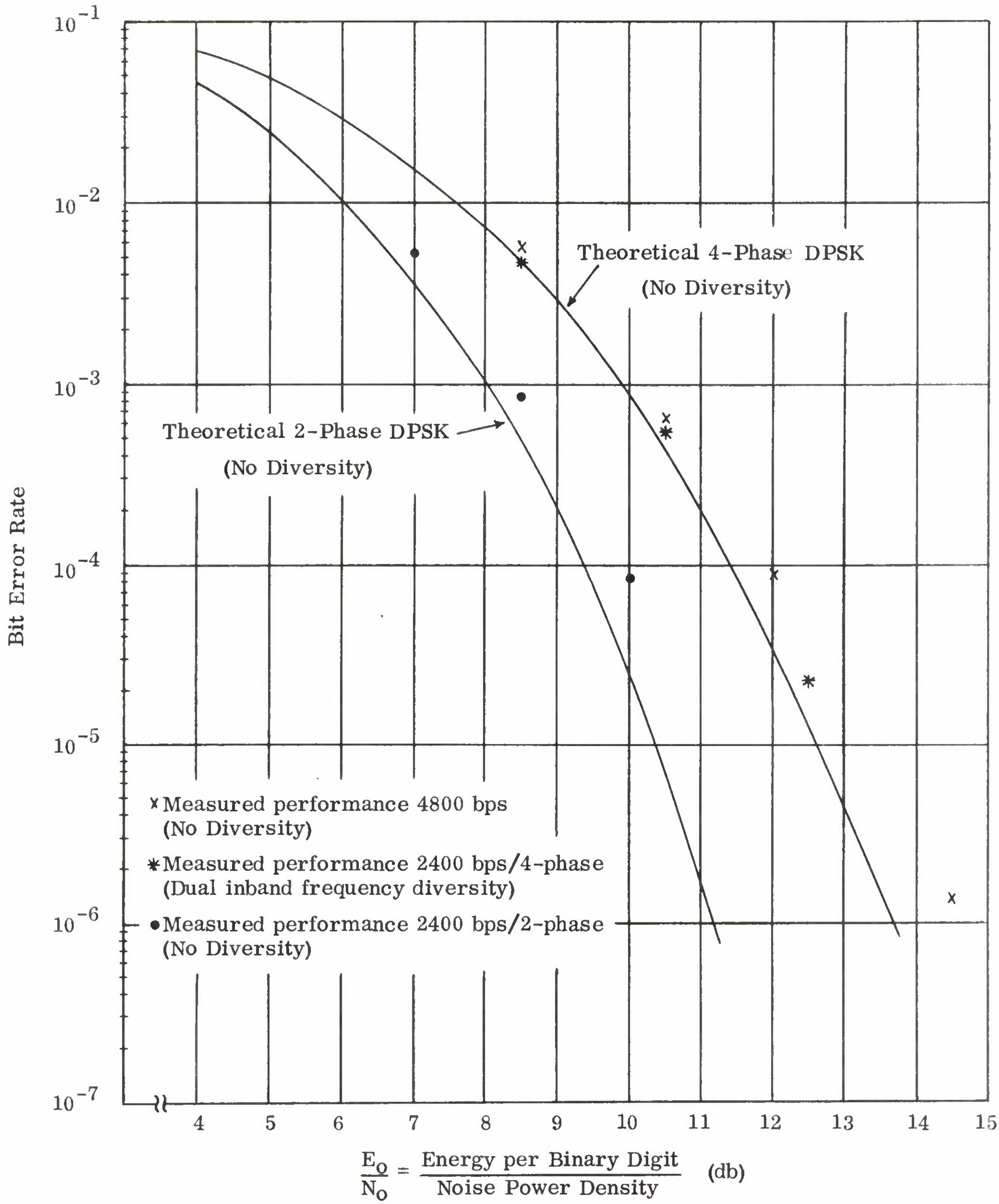


Figure 4. Back-to-Back ANDEFT/SC-320 Performance Verification

SECTION V

RESULTS

Introduction

The results of the laboratory tests are presented in families of parametric curves in Figures 5 through 22. Each family is identified by the mode of operation and fading bandwidth and can be cross-referenced to the Appendix, which contains all the raw data, by using the data/run identification numbers in Figure 3. The curve families appear in the order in which the data were taken. That is, the plotted values in Figures 5 and 6 were taken from data sheet 1, the plotted values in Figures 7 and 8 from data sheet 2, and so on.

Most of the curves in these families have the characteristic shape of "multipath limited" bit error rate curves, i.e., for low signal-to-noise ratios the channel error rate is nearly noise limited, whereas for high signal-to-noise ratios the channel is nearly multipath limited, or in other words the bit error rate cannot be further reduced by increasing signal-to-noise ratio. The bit error rate for these conditions is often called "irreducible". As the multipath delay spread is increased, the performance for any given mode of operation is degraded, i.e., the asymptotic behavior of the bit error rate curves appears at higher error rates. Some of the curves in Figures 5 through 22 which reach low values of BER (10^{-4} or less) have not reached an irreducible BER for a bit-energy-to-noise-density ratio of 40 db. This is especially true for the 2400 bps/4-phase mode of operation. Despite the lack of a true bottoming on some curves, signal-to-noise ratios as high as 40 db are normally characteristic of multipath-limited conditions. Therefore, for the purposes of this analysis, the measured BER at E_0/N_0 = 40 db will be treated as the multipath-limited BER and be so designated hereafter.

Some general observations from these curve families reveal that operation at 4800 bps with dual signal source diversity reception produces BER in the region of 10^{-5} to 10^{-3} for multipath-limited operation for delay spreads from 0.5 ms to 2 ms, respectively, and a fading bandwidth of 0.2 Hz. Nondiversity operation for the same set of conditions produces BER's in the range of 10^{-3} to 10^{-2}. The effect of increasing multipath delay spread is more severe than increasing fading bandwidth. Both reception and inband diversity produce substantial improvements in measured bit error rate. Two-phase modulation produces better results than four-phase modulation, however the 2400 bps/4-phase mode is superior to the 2400 bps/2-phase mode because of dual inband frequency diversity. A closer examination of the effect of increasing multipath delay spread and fading bandwidth, and an evaluation of the relative merits of diversity and two-phase operation are presented in the following sections.

Effect of Increasing Multipath Delay Spread

Each of the six modes of operation was examined for the effects of increasing multipath delay spread. This was accomplished by normalizing the multipath-limited BER's observed for T_d = 1, 2, and 5 ms to that observed for T_d = 0.5 ms for each mode of operation. The mean value of the resulting "degradation" factor was plotted as a function of multipath delay spread and the range of the observed values for all fading bandwidths was indicated by the vertical arrows. See Figures 23 through 28.

Nondiversity operation, that is, operation at 4800 bps or 2400 bps/2-phase produces a marked similarity in degradation for increasing multipath delay spreads as observed in Figures 24 and 28. The degradation factor exceeds one order of magnitude for values of T_d between 1 and 2 ms and two orders of magnitude for values of T_d between 4 and 5 ms. Next, a marked similarity in the effect of increasing multipath delay spread for diversity operation, viz., 4800 bps, 2400 bps/4-phase (inband diversity, only), and 2400 bps/2-phase, appears in Figures 23, 26, and 27, respectively. For these curves, a degradation of one order of magnitude is exceeded in the vicinity of $T_d = 1$ ms, two orders of magnitude for values of T_d between 2 and 3 ms, and three orders of magnitude for values of T_d in the vicinity of 4 ms. Finally, operation with 4-way diversity in the 2400 bps/4-phase mode which utilizes dual inband frequency diversity in addition to dual signal source diversity reception, shows an order of magnitude degradation between T_d of 0.5 and 1.0 ms, two orders of magnitude degradation between 1.5 and 2 ms, three orders at 3 ms, and 4 orders at 4 ms, approximately.

Diversity operation is more effective for small values of multipath delay spread. If all the data were normalized to the worst case multipath-limited BER, i.e., the BER observed for $T_d = 5$ ms, the greatest improvement factors would be observed for the smallest values of multipath delay spread as attested by this data. Despite the fact that larger degradations in BER are observed for the diversity operation, the net effect is not as severe as might be implied. For example, a degradation of nearly 5 orders of magnitude was observed for operation at 2400 bps/4-phase/diversity yet the resulting BER was still 5.5×10^{-3}.

A tendency to produce the smallest degradation at 0.2 Hz fading bandwidth was noted with 83% of the lowest values produced by this fading bandwidth. A tendency to produce the largest degradation at 2.0 Hz fading bandwidth was noted with 56% of the highest values produced by this fading bandwidth. The amount of degradation appeared to decrease as fading bandwidth increased with the predominant order 0.2, 0.5, and 2.0 Hz appearing in the data 50% of the time, and the order 0.5, 0.2, and 2.0 Hz appearing 28% of the time.

Effect of Increasing Fading Bandwidth

Each of the six modes of operation was examined for the effects of increasing fading bandwidth. This was accomplished by normalizing the multipath-limited BER's observed at fading bandwidths of 0.5 and 2.0 Hz to that observed at 0.2 Hz for each mode. The mean value of the resulting "degradation" factor was plotted as a function of fading bandwidth and the range of the observed values for all fading bandwidths was indicated by vertical arrows. See Figures 29 through 34.

The degradation of performance due to increasing fading bandwidth to 2.0 Hz exceeded one order of magnitude in only two cases. This occurred for operation at 4800 bps with diversity ($T_d = 0.5$ ms and $f_b = 2.0$ Hz) and 2400 bps/4-phase with diversity ($T_d = 0.5$ ms and $f_b = 2.0$ Hz). A tendency to produce a slight improvement in performance for a fading bandwidth of 0.5 Hz was noted for operation at 4800 bps and 2400 bps/4-phase, although for the most part performance was essentially equivalent. Mean values of degradation for fading bandwidth of 2.0 Hz ranged from just under 2 times to just over 20 times, while degradation or improvement for a fading bandwidth of 0.5 Hz was negligible.

Evaluation of Operating Modes

In order to compare the various operating modes, seven improvement factors were defined, and values were computed for the multipath-limited cases as follows:

$$A = \frac{\text{BER at 4800 bps/nondiversity}}{\text{BER at 4800 bps/diversity}}$$

$$B = \frac{\text{BER at 4800 bps/nondiversity}}{\text{BER at 2400 bps/4-phase/nondiversity*}}$$

$$C = \frac{\text{BER at 4800 bps/nondiversity}}{\text{BER at 2400 bps/2-phase/nondiversity}}$$

$$D = \frac{\text{BER at 4800 bps/diversity}}{\text{BER at 2400 bps/4-phase/diversity*}}$$

$$E = \frac{\text{BER at 4800 bps/nondiversity}}{\text{BER at 2400 bps/2-phase/diversity}}$$

$$F = \frac{\text{BER at 4800 bps/nondiversity}}{\text{BER at 2400 bps/4-phase/diversity*}}$$

$$G = \frac{\text{BER at 4800 bps/nondiversity}}{\text{BER at 2400 bps/2-phase/diversity}}$$

*Includes dual inband frequency diversity.

The mean value of improvement factor for all values of fading bandwidth was determined and is plotted as a function of multipath delay spread in Figures 35 through 41 for factors A through G, respectively. For each plotted value, the range of the computed values is indicated by the vertical arrows.

Overall, a tendency to produce the largest improvement factor was noted for a fading bandwidth of 0.2 Hz (54% of the samples). A tendency to produce the smallest improvement factor was noted for a fading bandwidth of 2.0 Hz (57% of the samples). The widest range of improvement factors was observed for a multipath delay spread of 0.5 ms and the narrowest range of improvement factors was noted for a multipath delay spread of 5.0 ms. Also, the predominant order of arrangement, smallest to largest (observed in 36% of the cases), was 2.0, 0.5, and 0.2 Hz, respectively.

Several other observations were made from the data in Figures 35 through 41 as follows:

(A) See Figure 35. Reception diversity as implemented in the ANDEFT/SC-320 has increasing value for decreasing multipath delay spreads. Improvement factors extend over the range of 2 to 140, approximately, for multipath delay spreads of 5 ms to 0.5 ms, respectively. The greatest increase is noted between $T_d = 2$ ms and 0.5 ms, where improvement factor increases by over one order of magnitude.

(B) See Figure 36. Inband frequency diversity as implemented in ANDEFT, although it requires that the data throughput rate be reduced to one-half, produced improvement factors in the range of 4 to over 400 for multipath delay spreads of 5 ms to 0.5 ms, and the data shows that this method of diversity is slightly more effective for the HF simulated path conditions than the reception diversity technique (A).

(C) See Figure 37. Two-phase operation has only limited value for the multipath-limited cases as shown by the fact that the average improvement factor never reaches a value much over one order of magnitude.

(D) See Figure 38. When dual inband frequency diversity is added to reception diversity, the improvement factors produced are approximately the same as those for the nondiversity situation (B) except at low values of multipath delay spread where improvement factor appears to suffer, especially for a multipath delay spread of 1 ms.

(E) See Figure 39. When two-phase diversity operation is compared with four-phase diversity operation, improvement factors are somewhat larger than without diversity (C), but still never exceed a value much over 25.

(F) See Figure 40. When the performance at 2400 bps/4-phase which includes dual inband frequency diversity, is compared with the nondiversity 4800 bps modes, improvement factors extending to over 4 orders of magnitude are produced for small multipath delay spreads. Even at large multipath delay spreads (5 ms), a factor of 10 is produced.

(G) See Figure 41. The comparison of the 2400 bps/2-phase mode with 4800 bps nondiversity operation shows improvement factors exceeding two orders of magnitude for a multipath delay spread of 0.5 ms. But mode for mode, it takes a second place to the 2400 bps/4-phase mode which utilizes 4-way diversity.

The factors A, B, and C which relate performance to the basic 4800 bps nondiversity mode, rank in the order of increasing effectiveness: C, A, and B. See Figure 42. The factors D, E, F, and G which relate performance to the 4800 bps diversity mode, rank in order of increasing effectiveness: E, D, G, and F. See Figure 43. The factors D and E overlap considerably with A and B as expected.

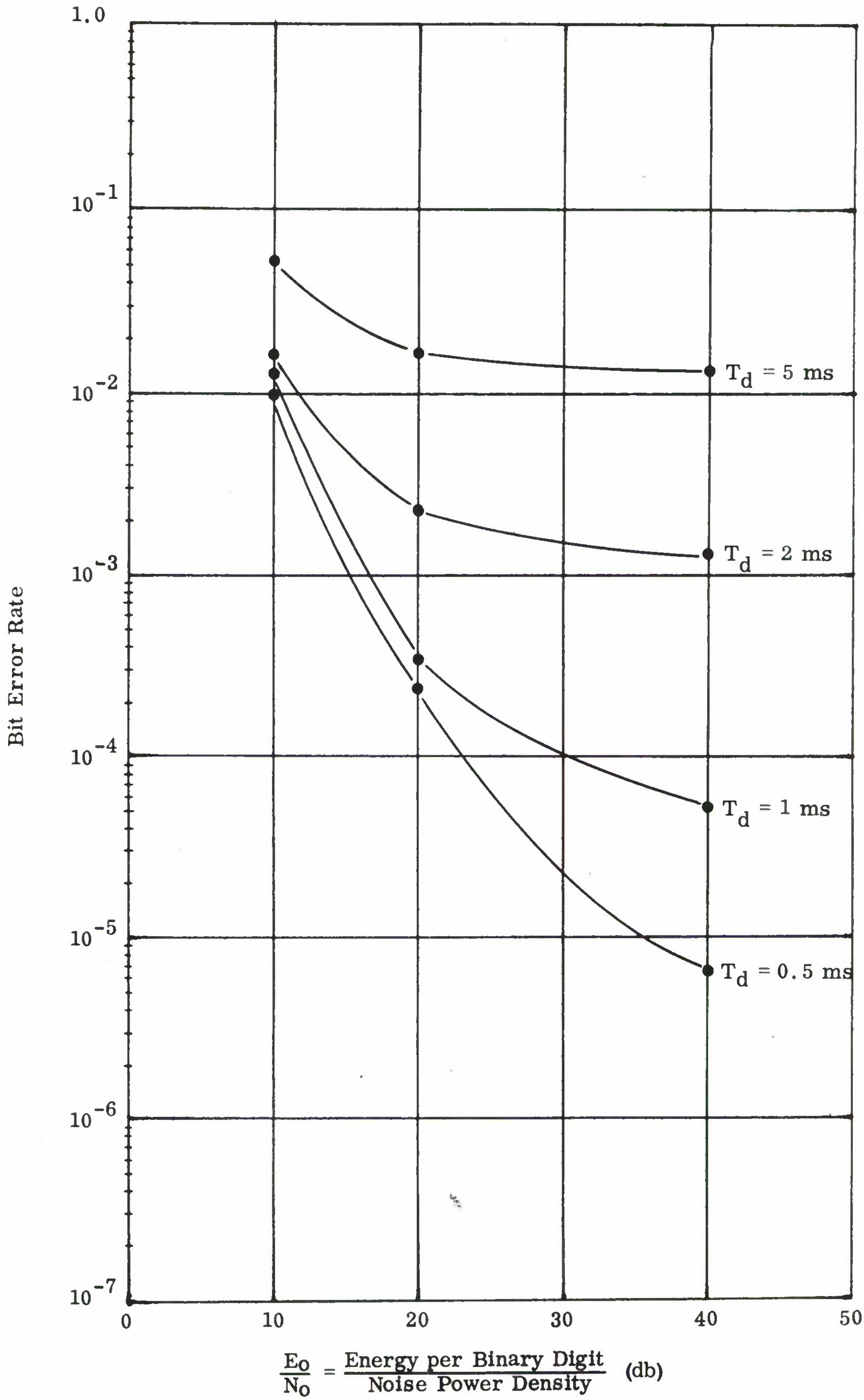


Figure 5. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, f_b = 0.2 Hz, 4800 bps, Diversity

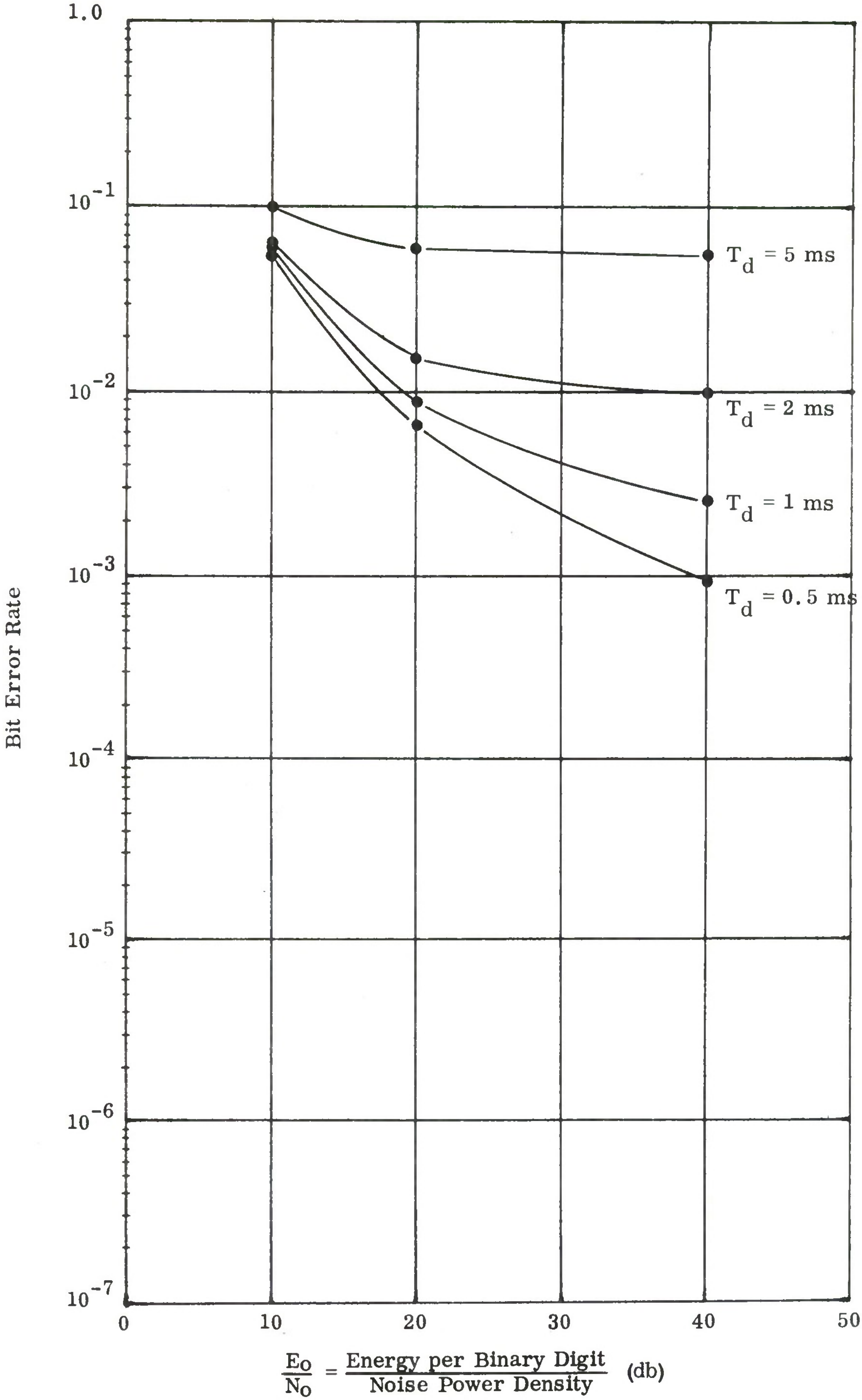


Figure 6. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, f_b = 0.2 Hz, 4800 bps, Nondiversity

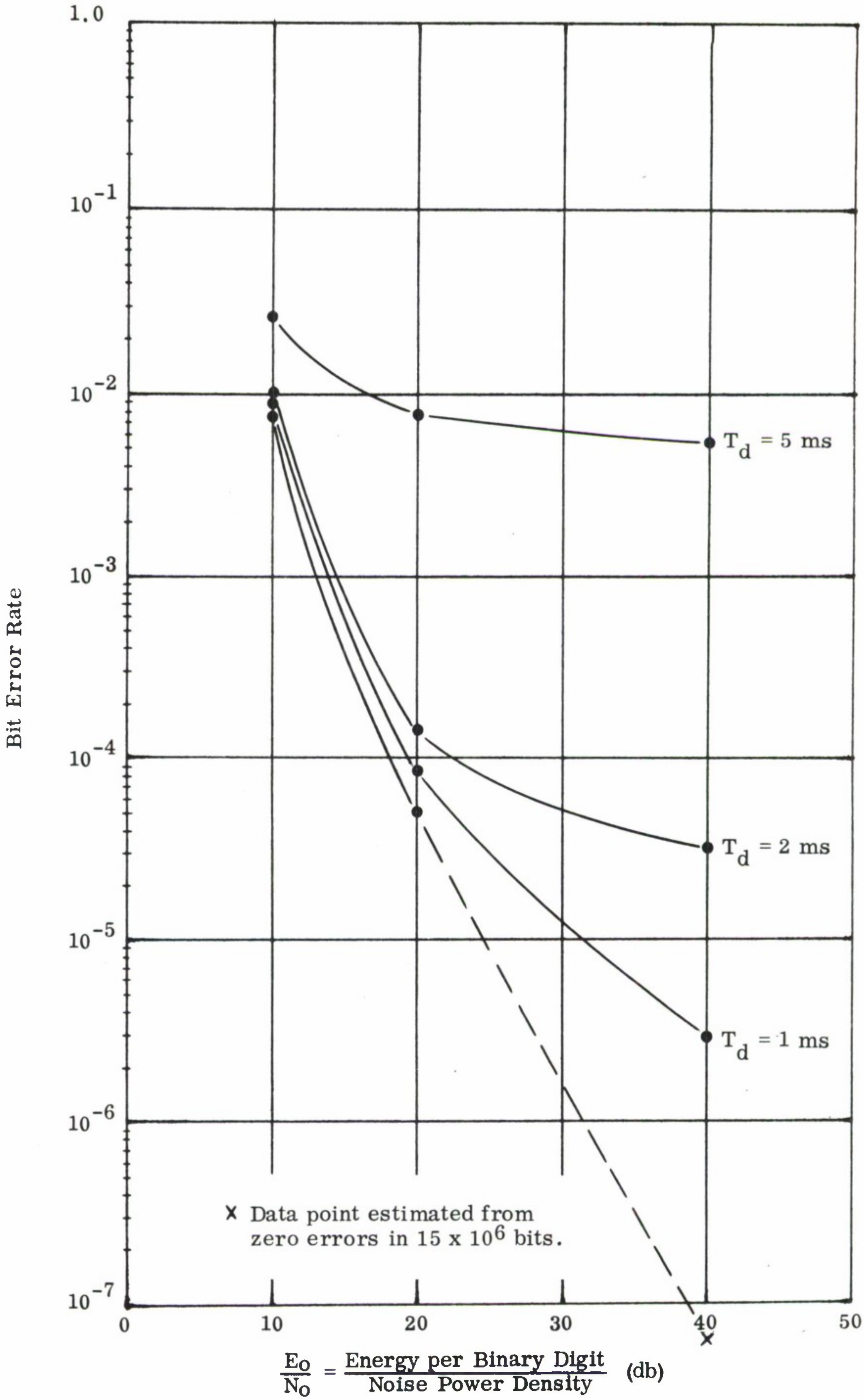


Figure 7. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, f_b = 0.2 Hz, 2400 bps/4-phase, Diversity

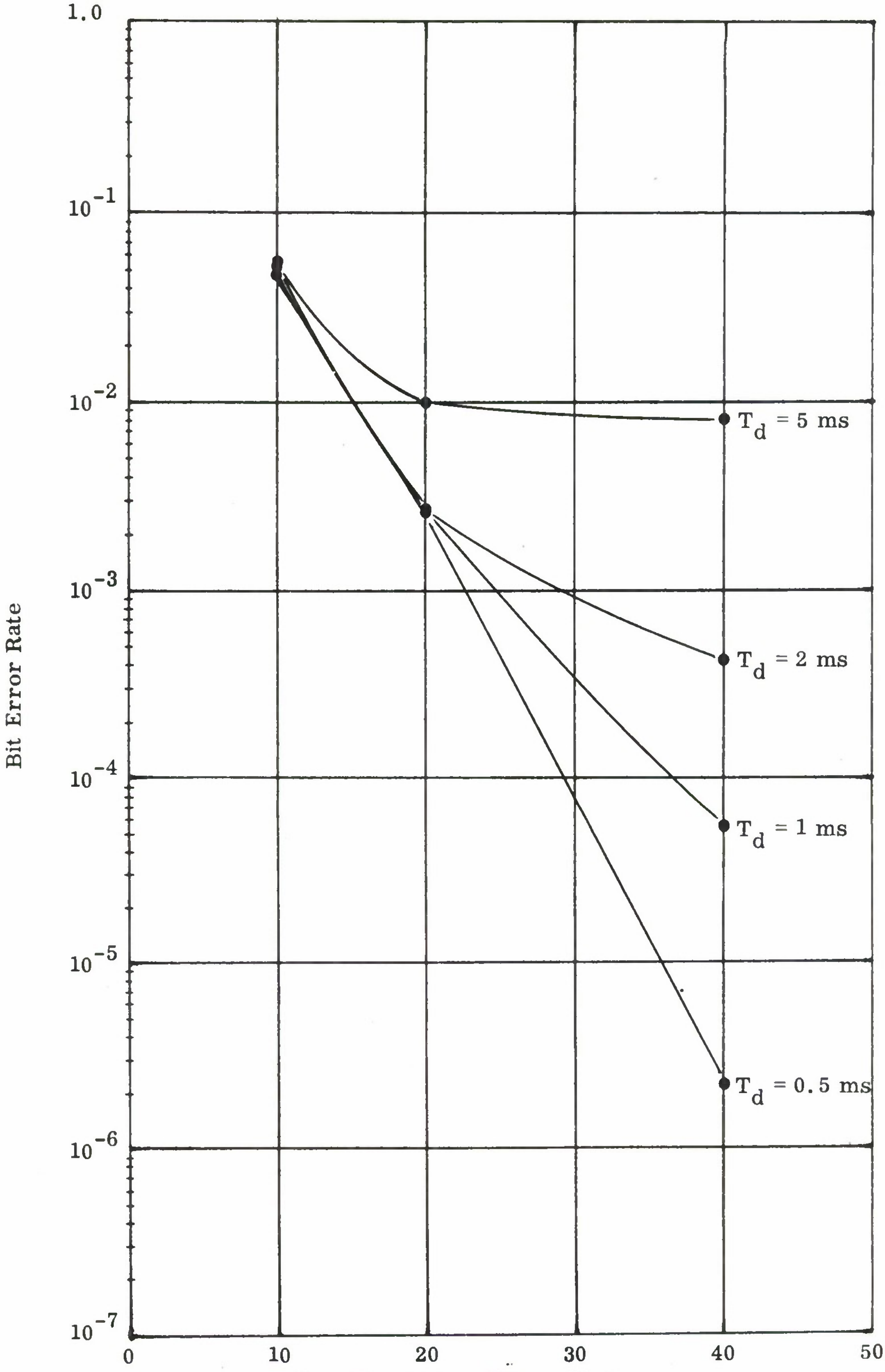


Figure 8. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, f_b = 0.2 Hz, 2400 bps/4-phase, Nondiversity

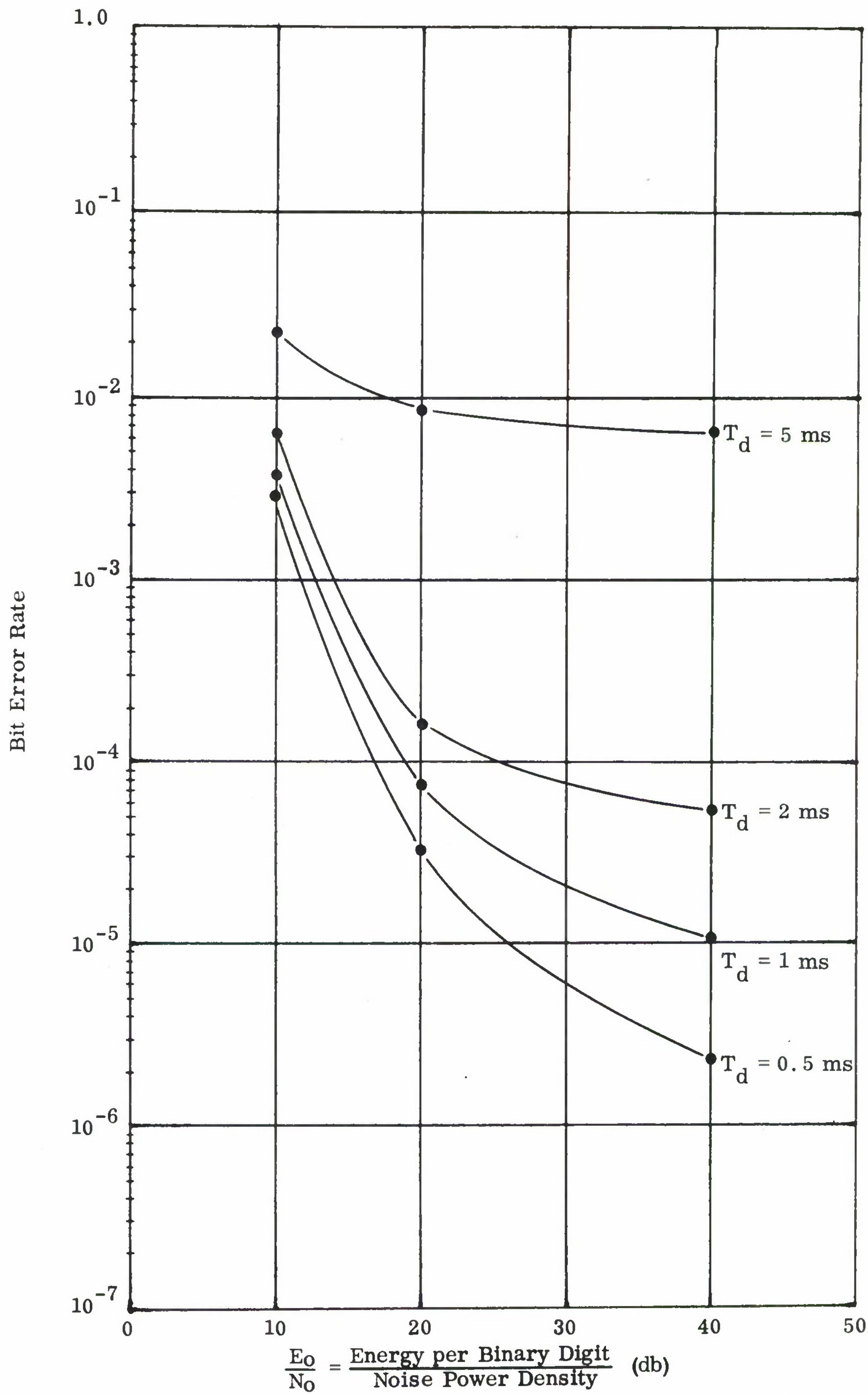


Figure 9. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, $f_b = 0.2$ Hz, 2400 bps/2-phase, Diversity

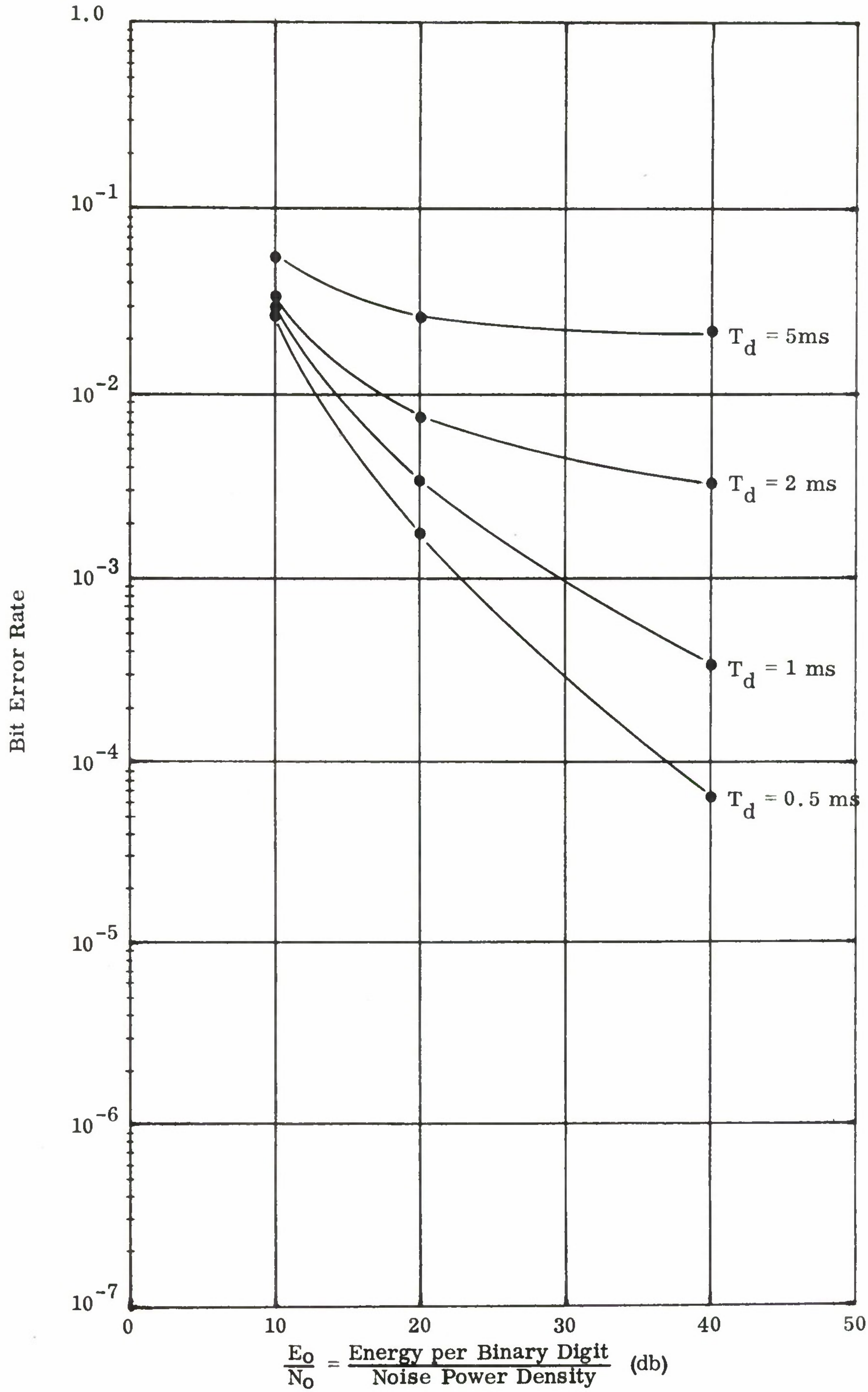


Figure 10. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, $f_b = 0.2$ Hz, 2400 bps/2-phase, Nondiversity

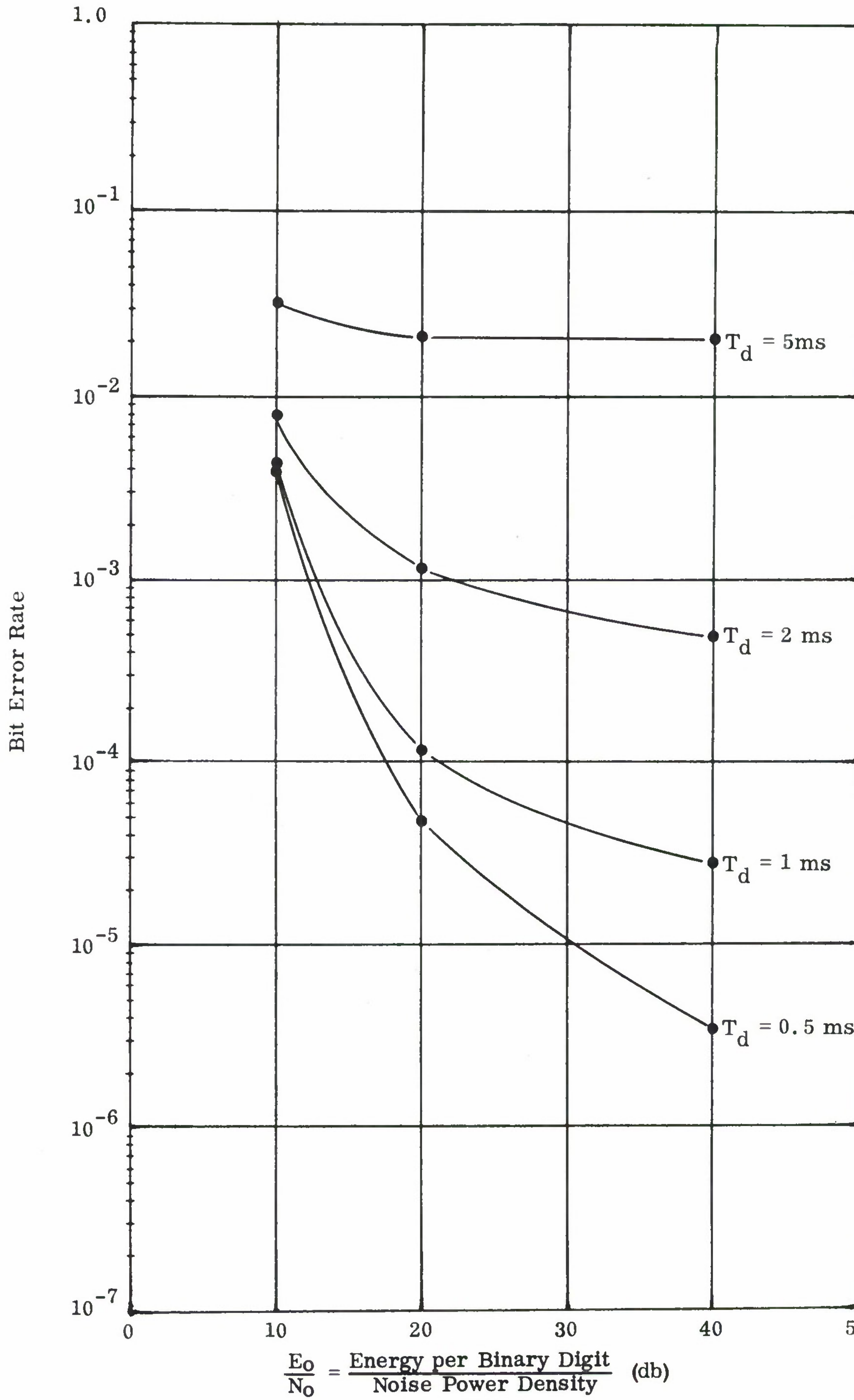


Figure 11. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, f_b = 0.5 Hz, 4800 bps, Diversity

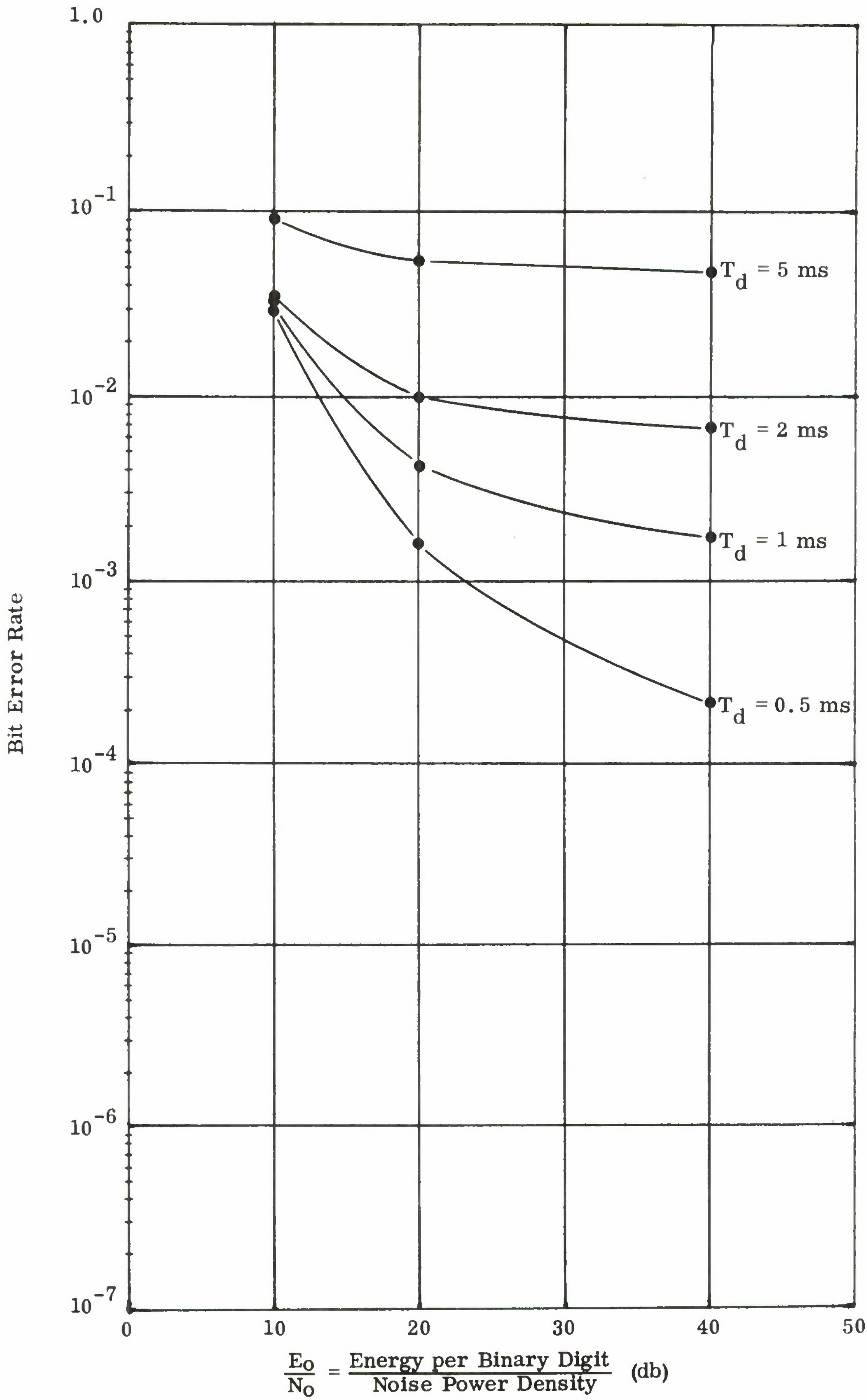


Figure 12. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, f_b = 0.5 Hz, 4800 bps, Nondiversity

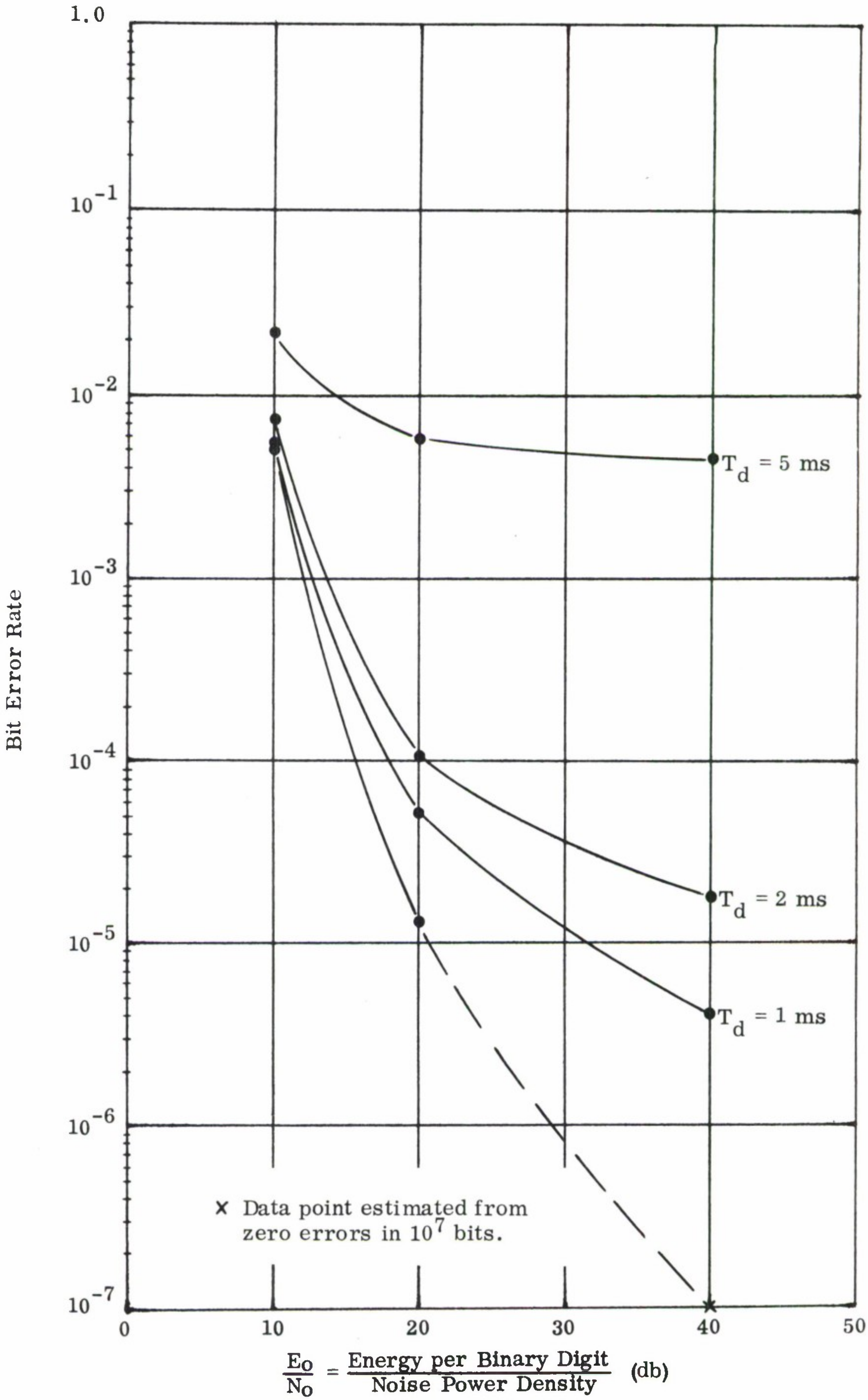


Figure 13. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, f_b = 0.5 Hz, 2400 bps/4-phase, Diversity

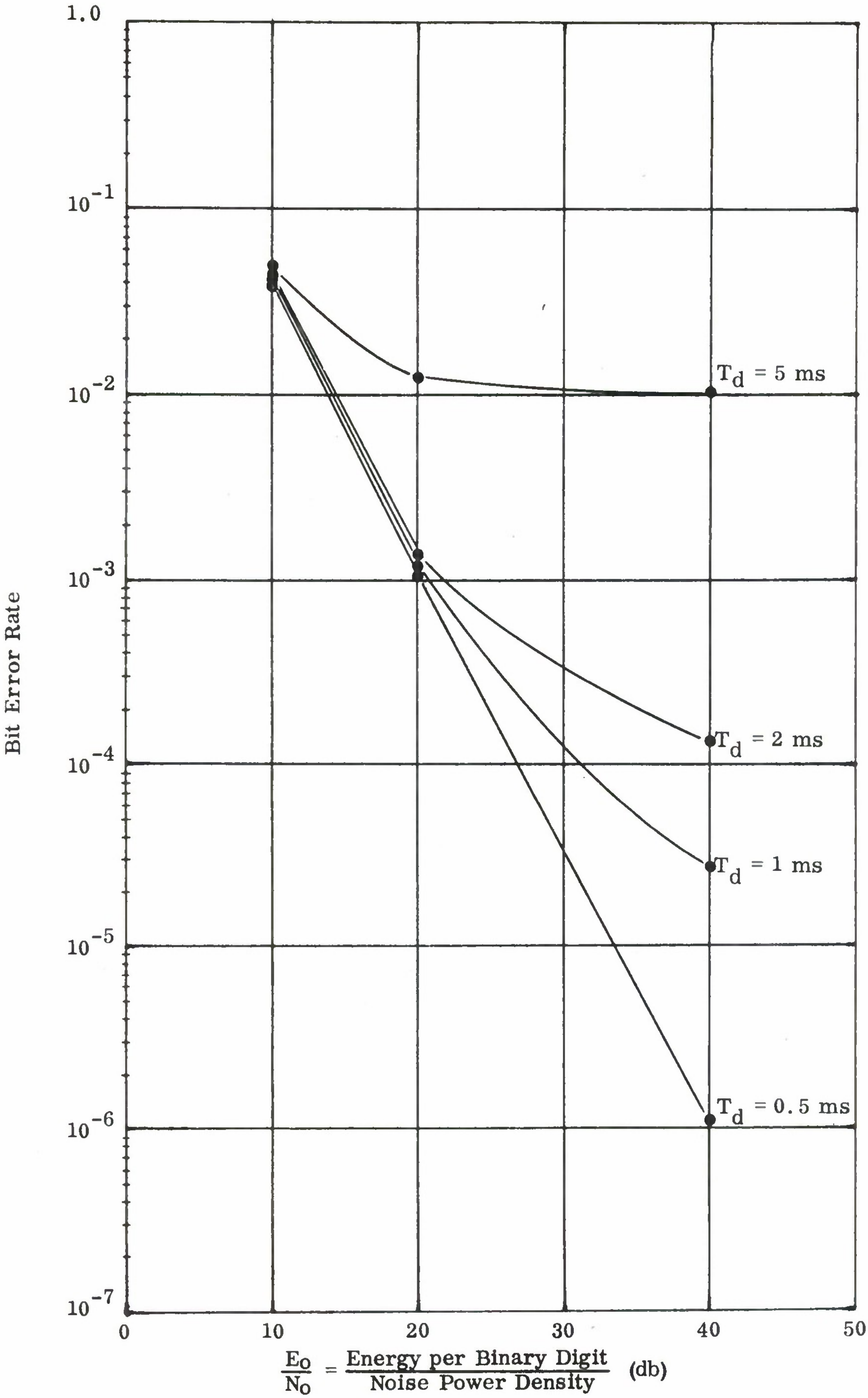


Figure 14. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, $f_b = 0.5$ Hz, 2400 bps/4-phase, Nondiversity

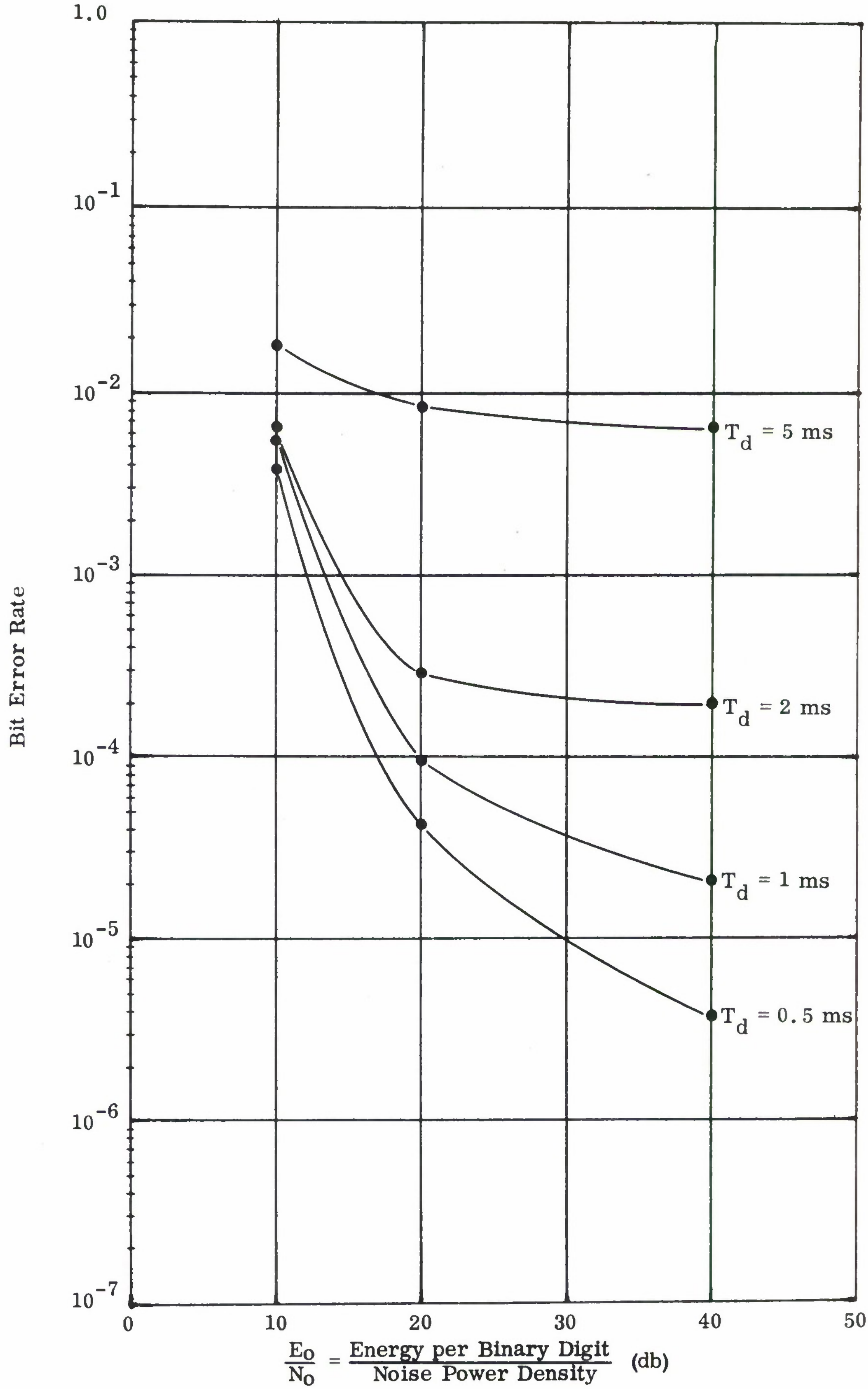


Figure 15. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, f_b = 0.5 Hz, 2400 bps/2-phase, Diversity

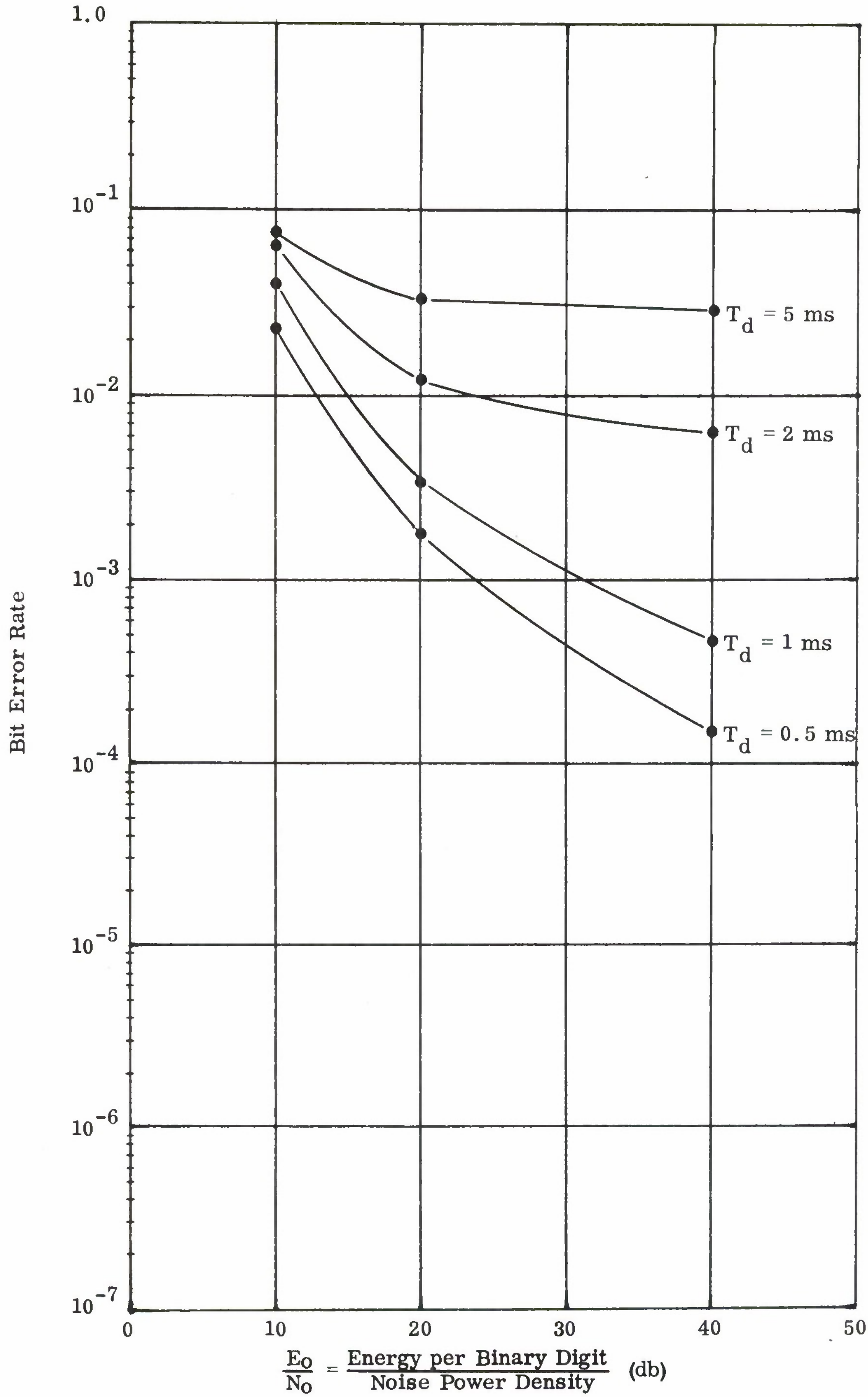


Figure 16. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, f_b = 0.5 Hz, 2400 bps/2-phase, Nondiversity

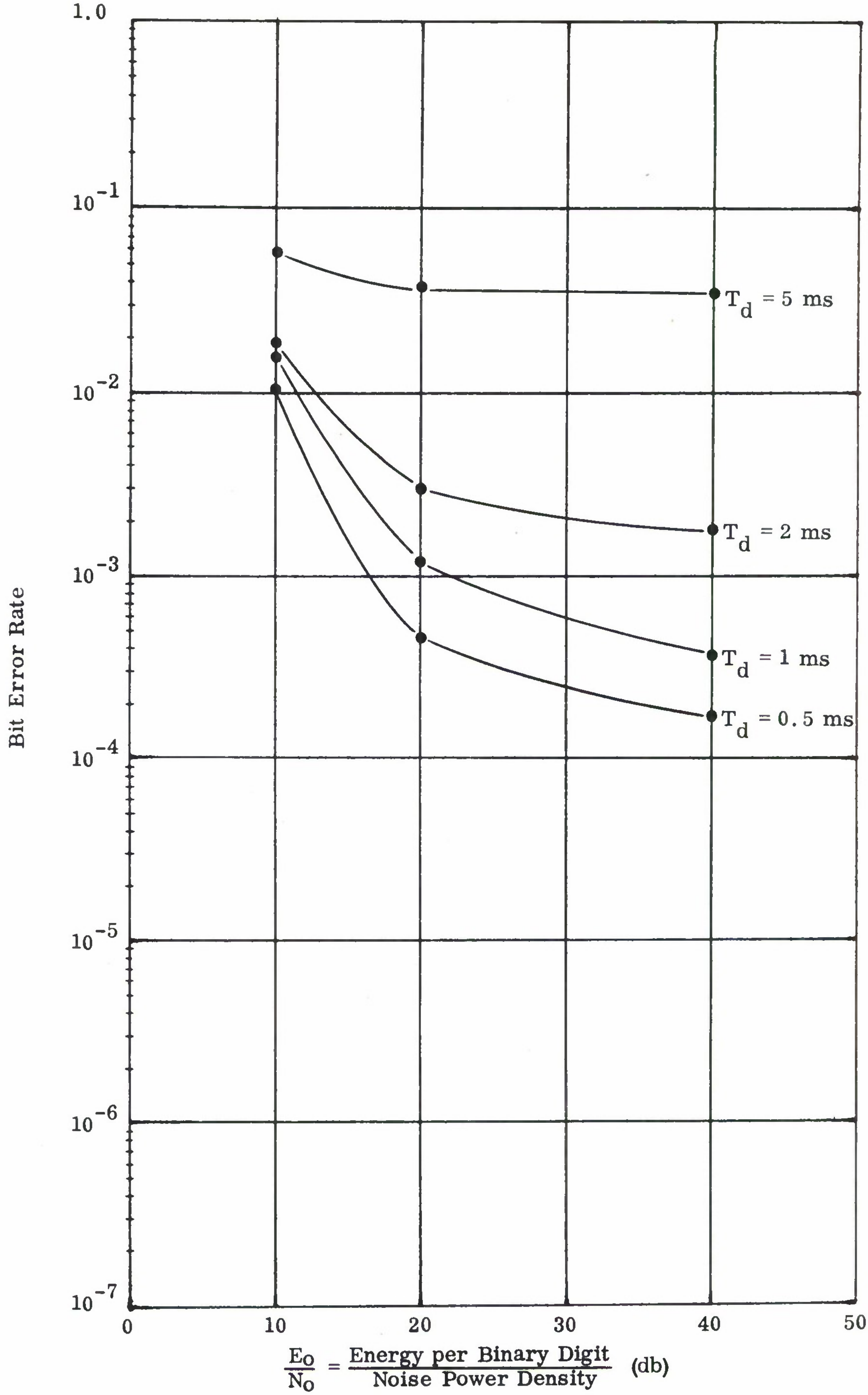


Figure 17. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, f_b = 2.0 Hz, 4800 bps, Diversity

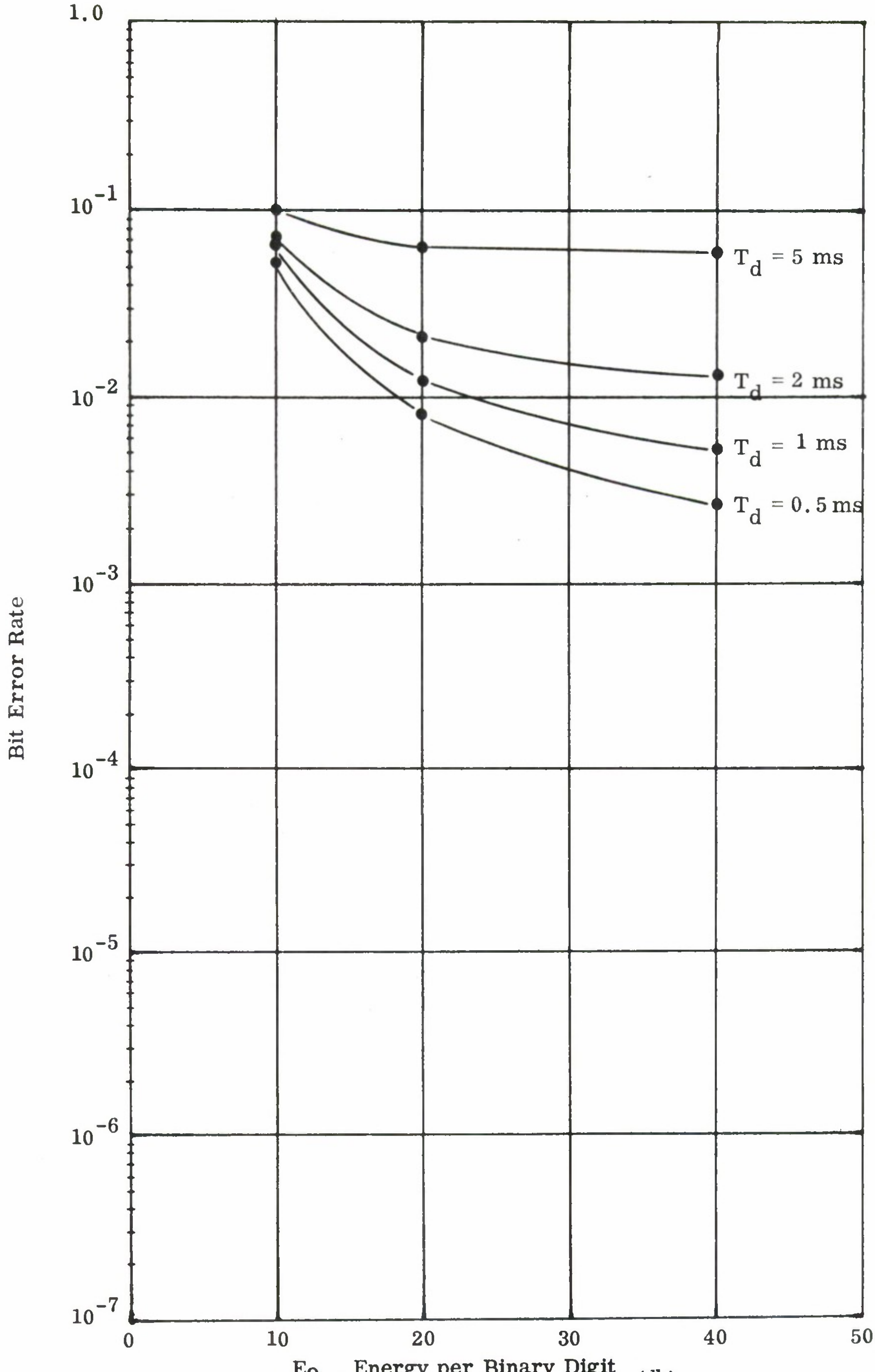


Figure 18. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, f_b = 2.0 Hz, 4800 bps, Nondiversity

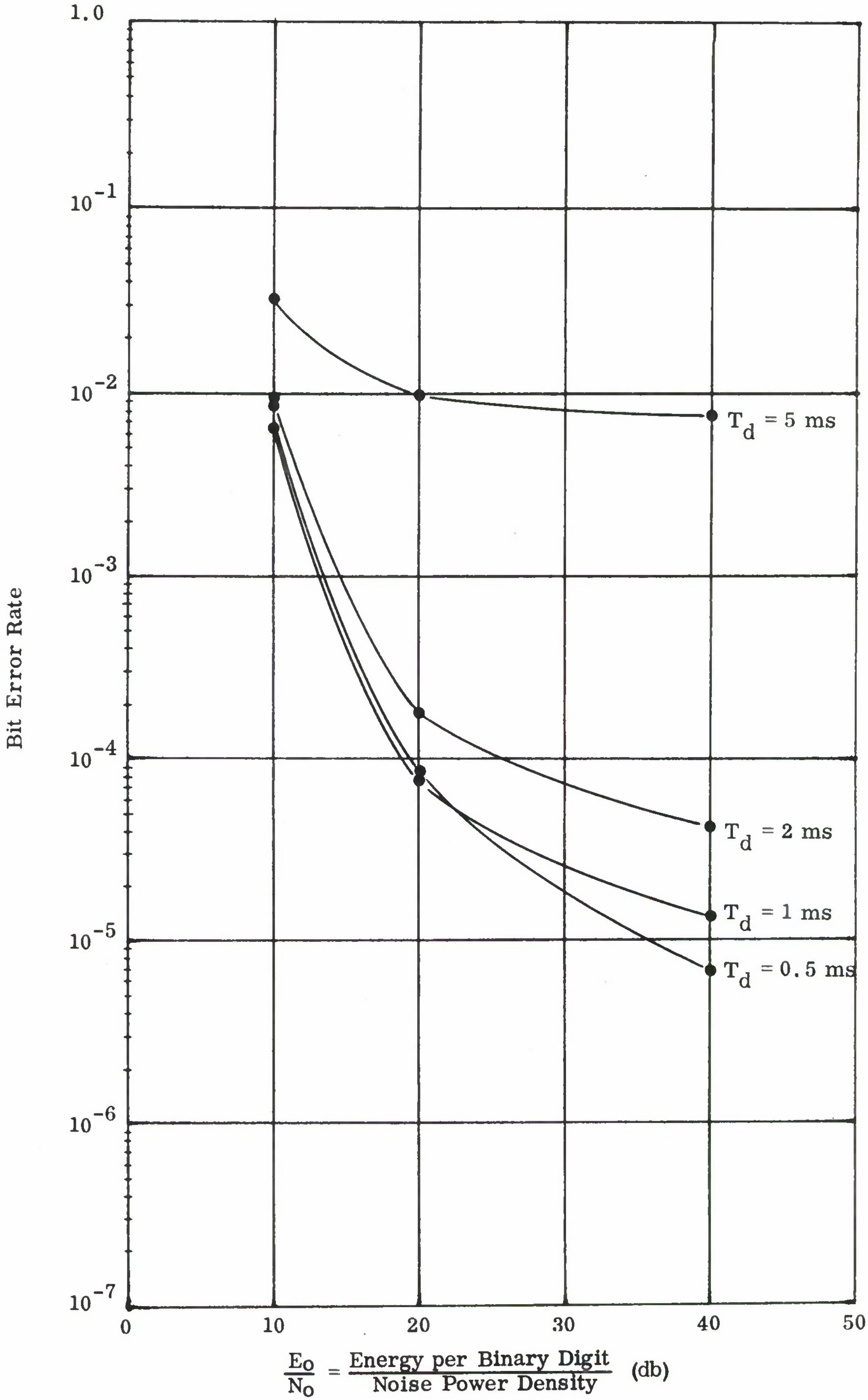


Figure 19. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, f_b = 2.0 Hz, 2400 bps/4-phase, Diversity

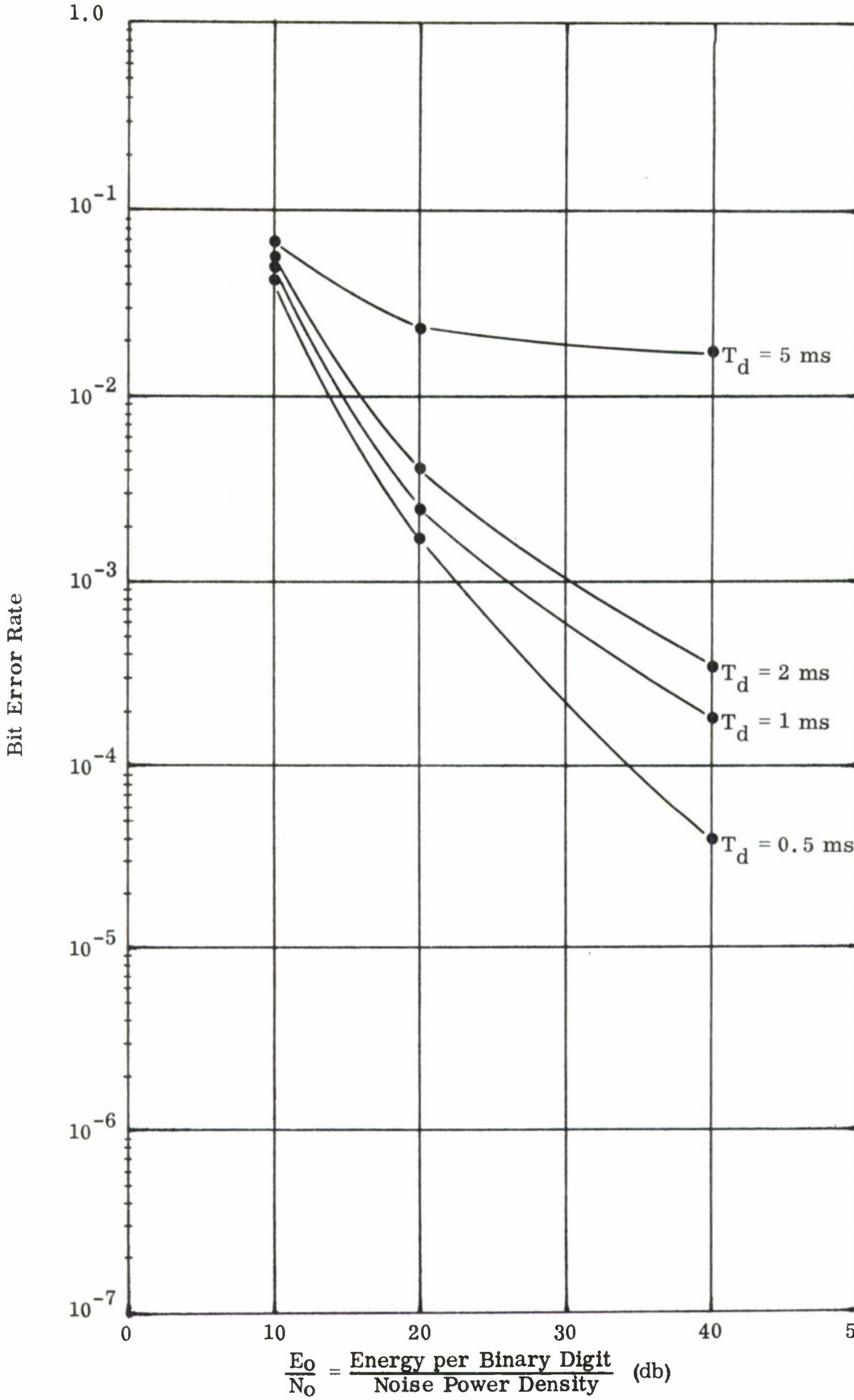


Figure 20. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, f_b = 2.0 Hz, 2400 bps/4-phase, Nondiversity

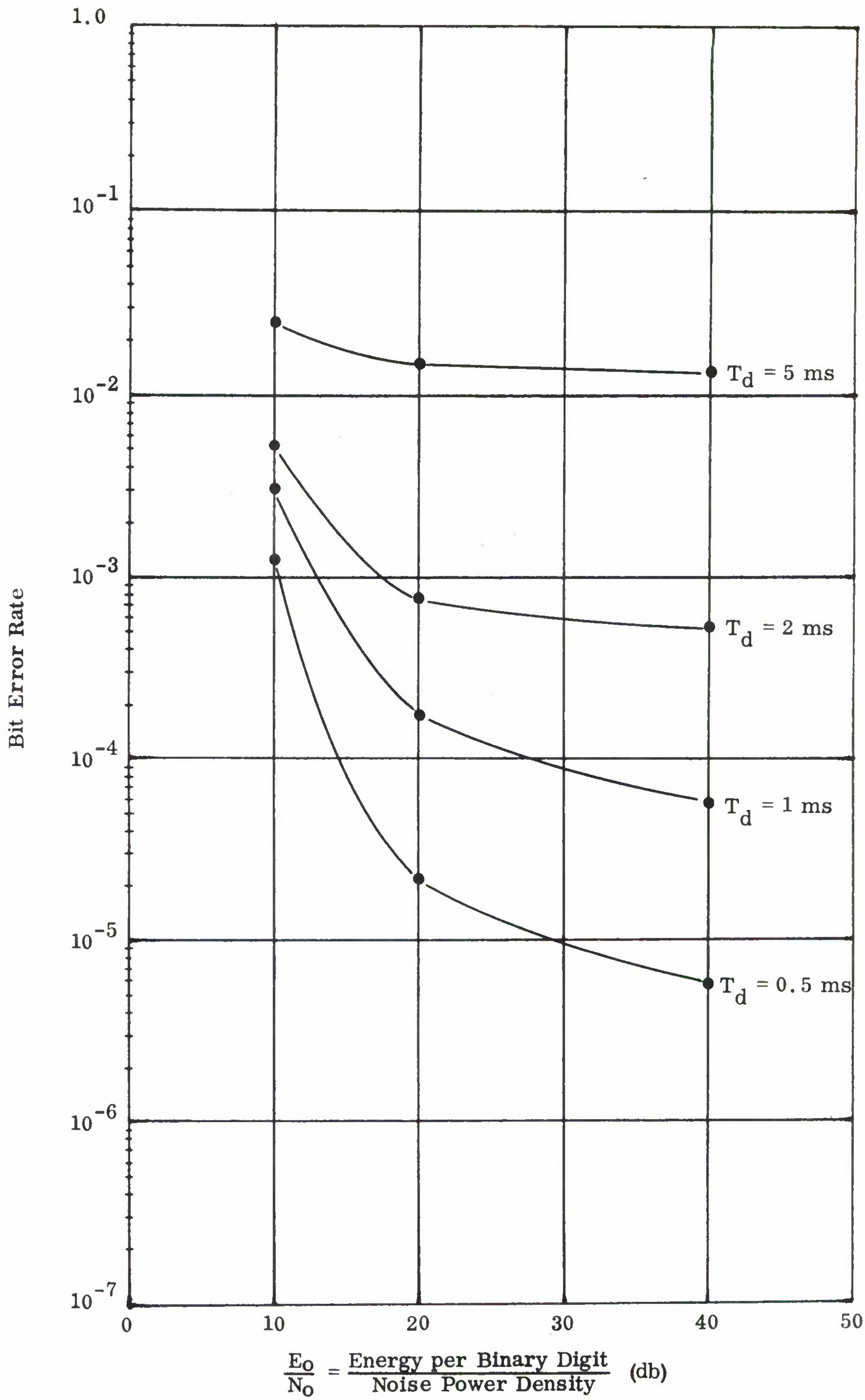


Figure 21. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, f_b = 2.0 Hz, 2400 bps/2-phase, Diversity

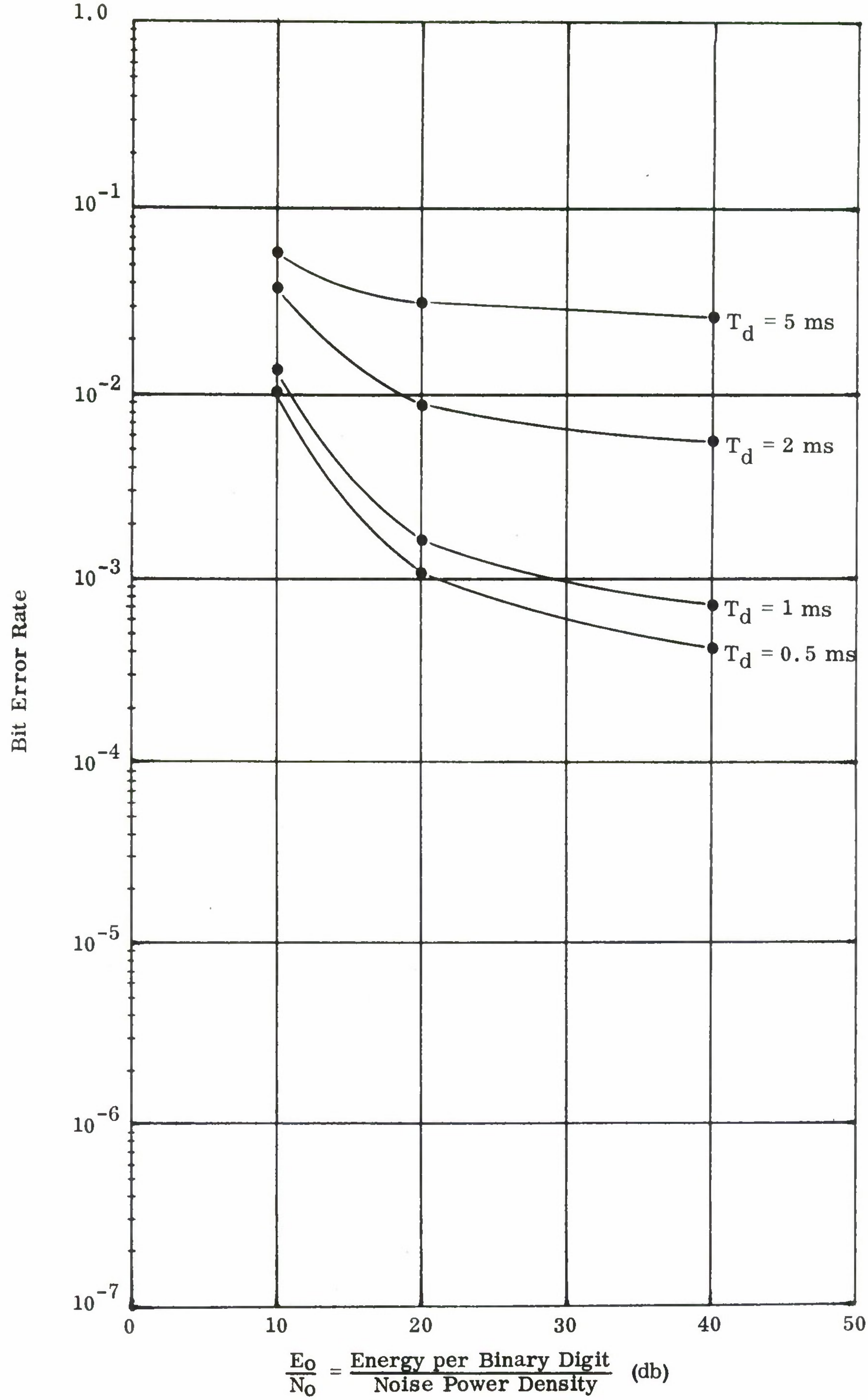
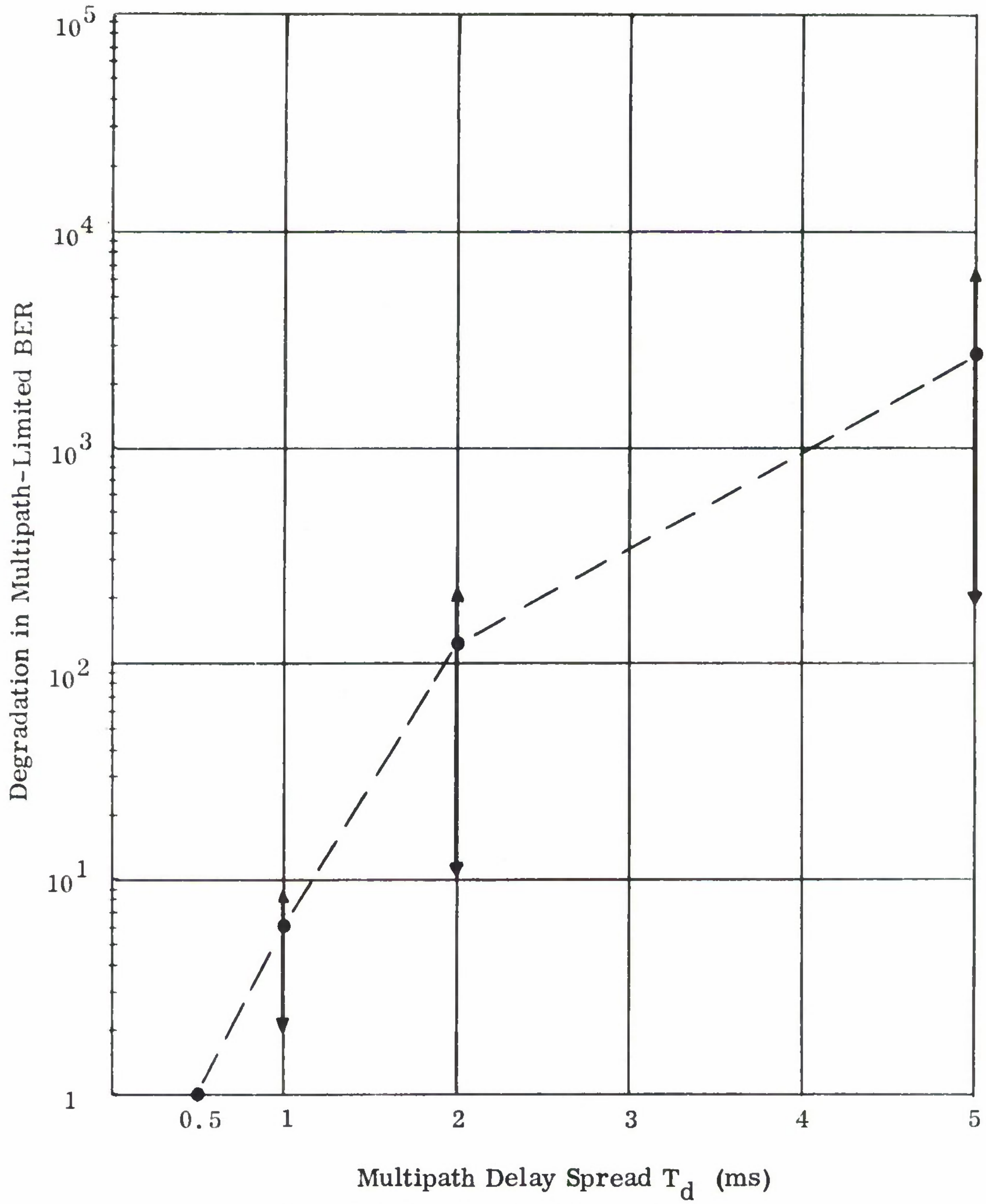
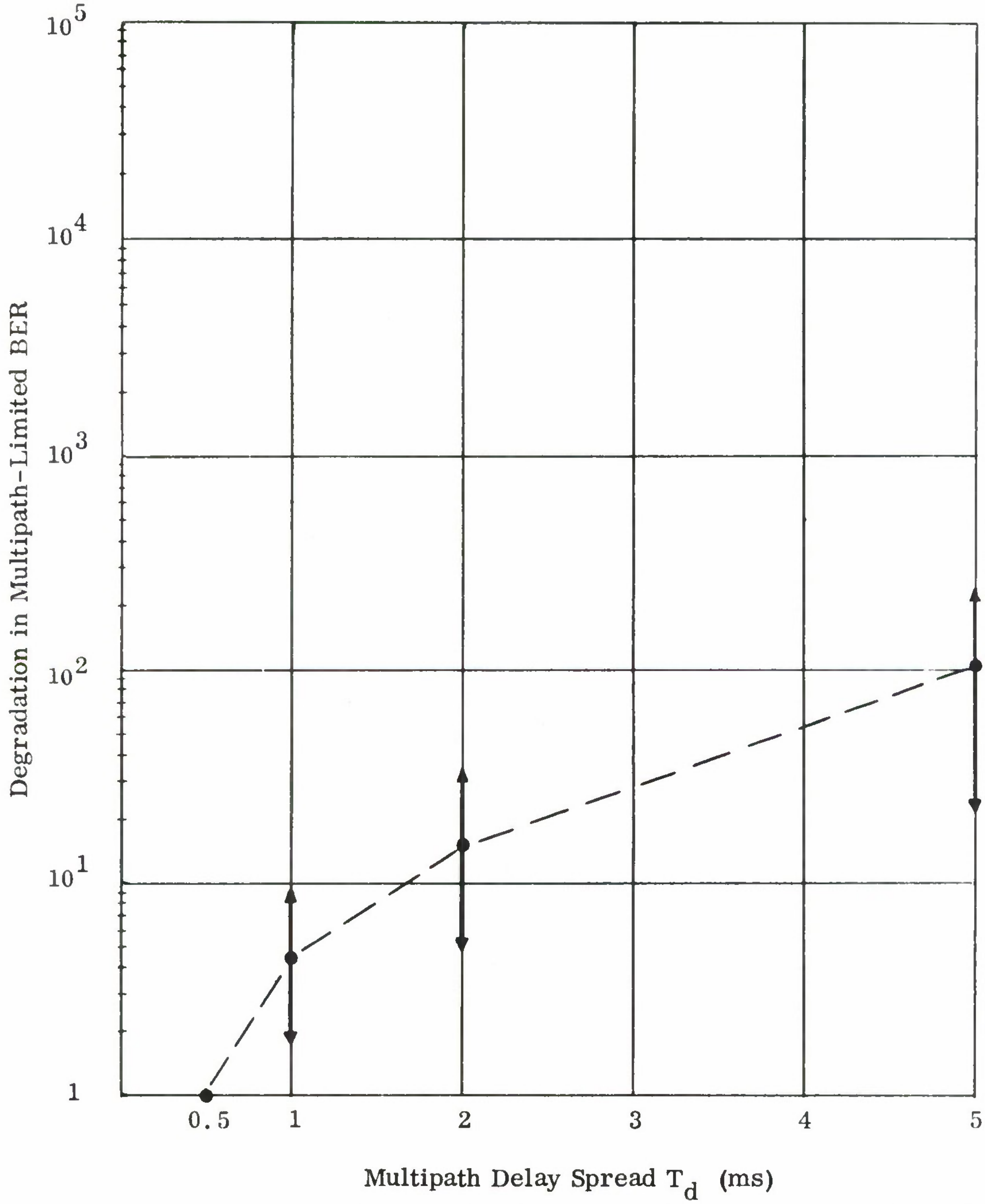


Figure 22. ANDEFT/SC-320 Performance for Simulated HF Path Conditions, f_b = 2.0 Hz, 2400 bps/2-phase, Nondiversity



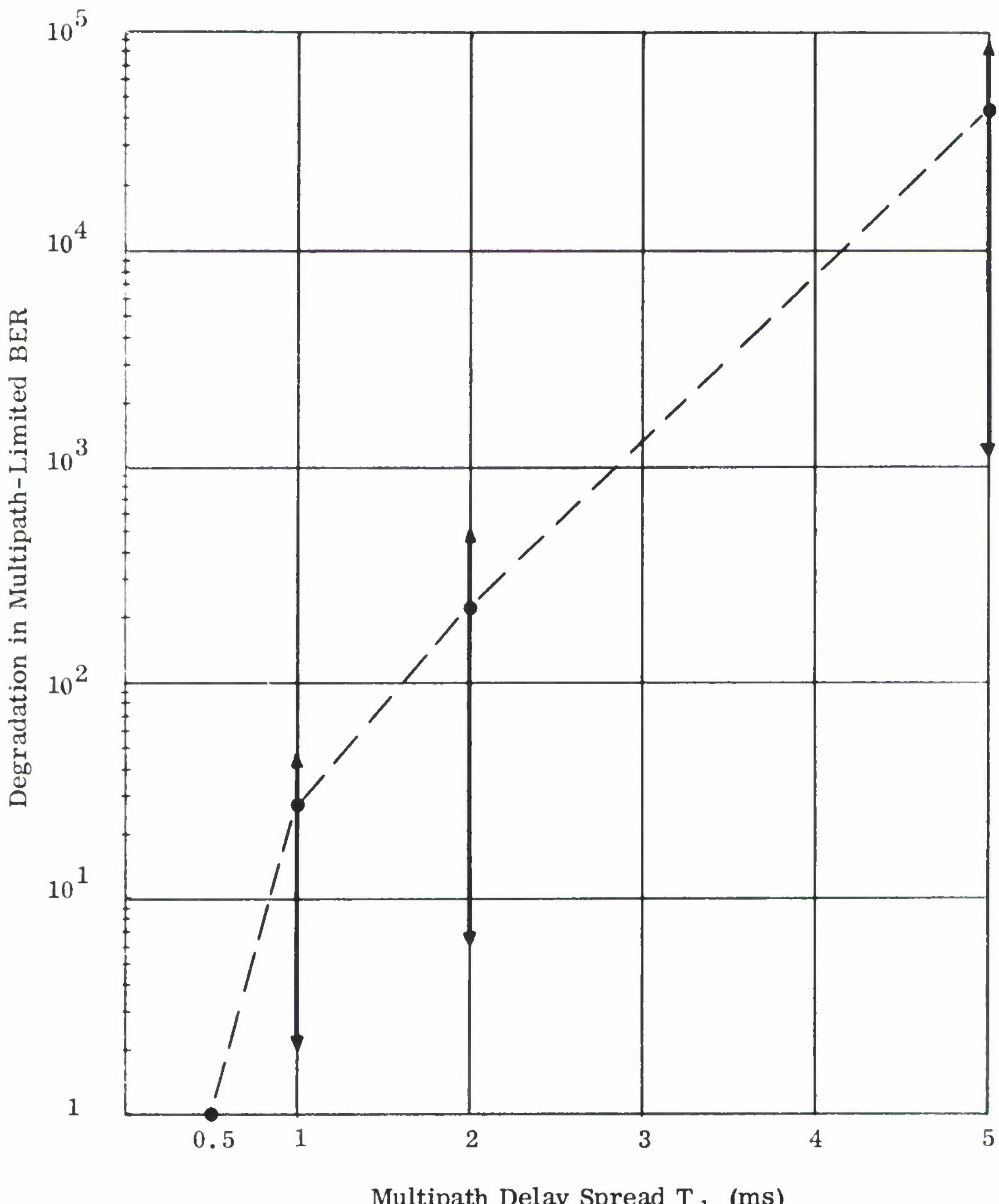
● Mean value for all fading bandwidths. All data normalized to 0.5 ms multipath delay spread.

Figure 23. Degradation in Multipath-Limited BER as a Function of Multipath Delay Spread, 4800 bps, Diversity



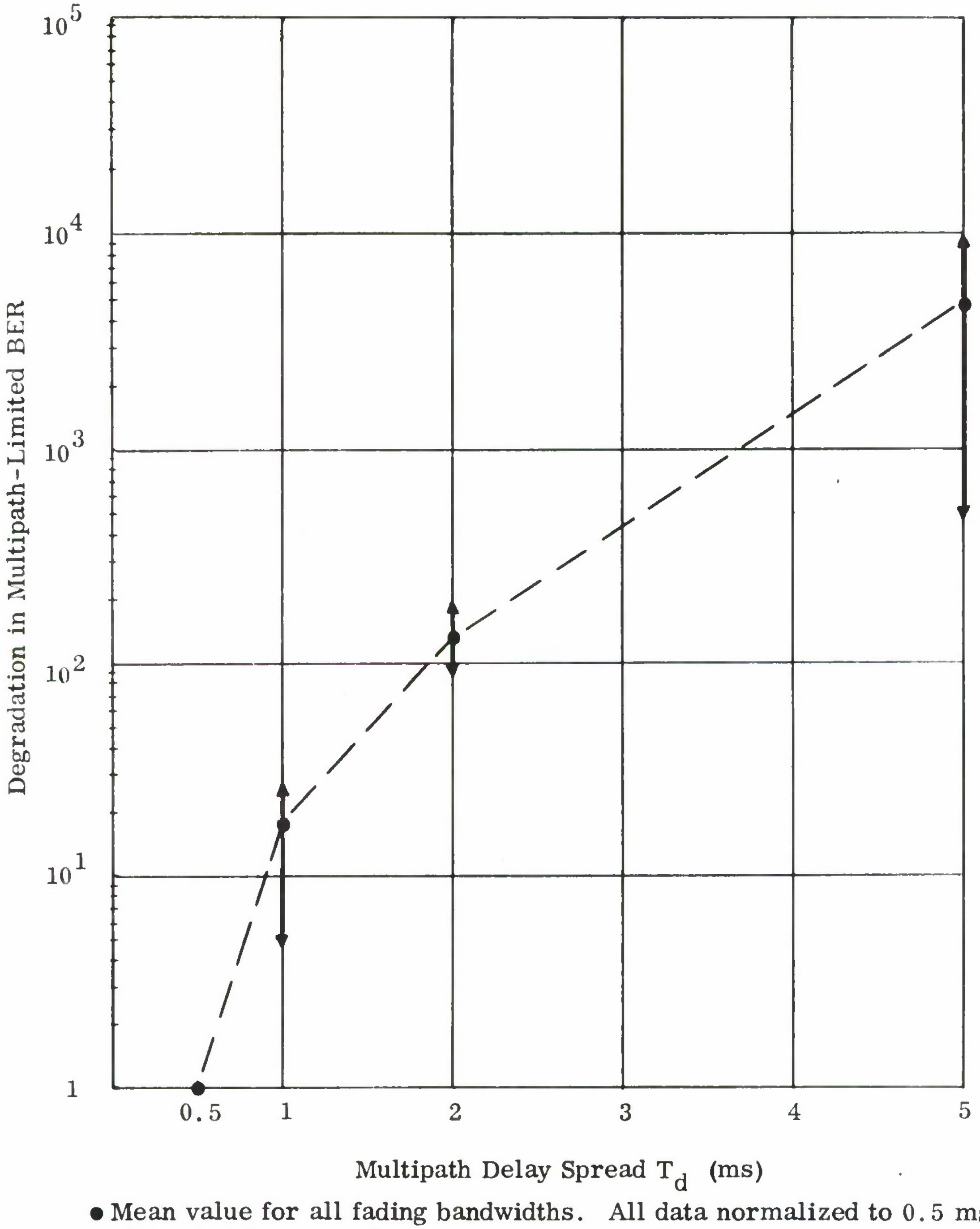
● Mean value for all fading bandwidths. All data normalized to 0.5 ms multipath delay spread.

Figure 24. Degradation in Multipath-Limited BER as a Function of Fading Bandwidth, 4800 bps, Nondiversity



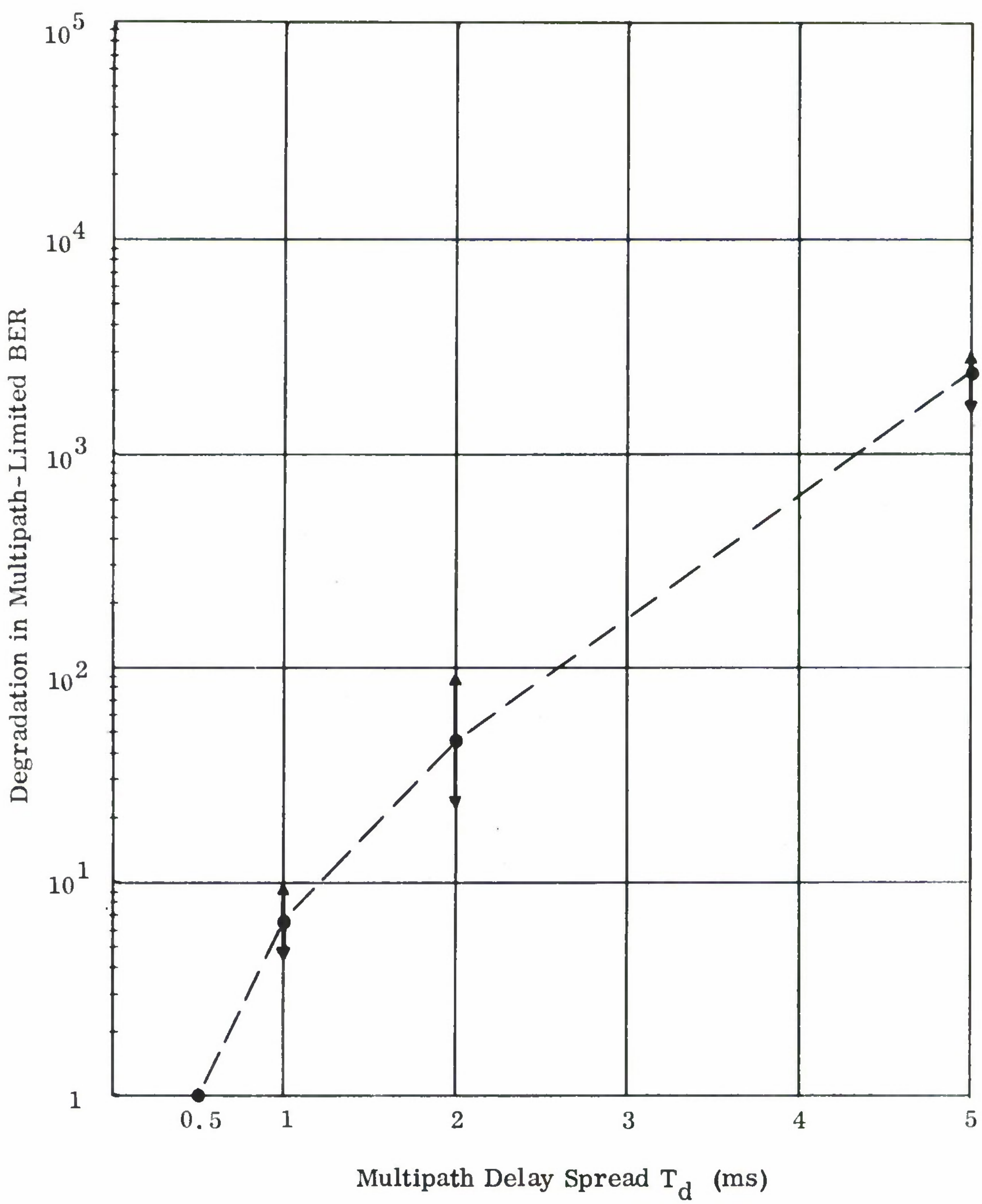
● Mean value for all fading bandwidths. All data normalized to 0.5 ms multipath delay spread.

Figure 25. Degradation in Multipath-Limited BER as a Function of Multipath Delay Spread, 2400 bps/4-phase, Diversity



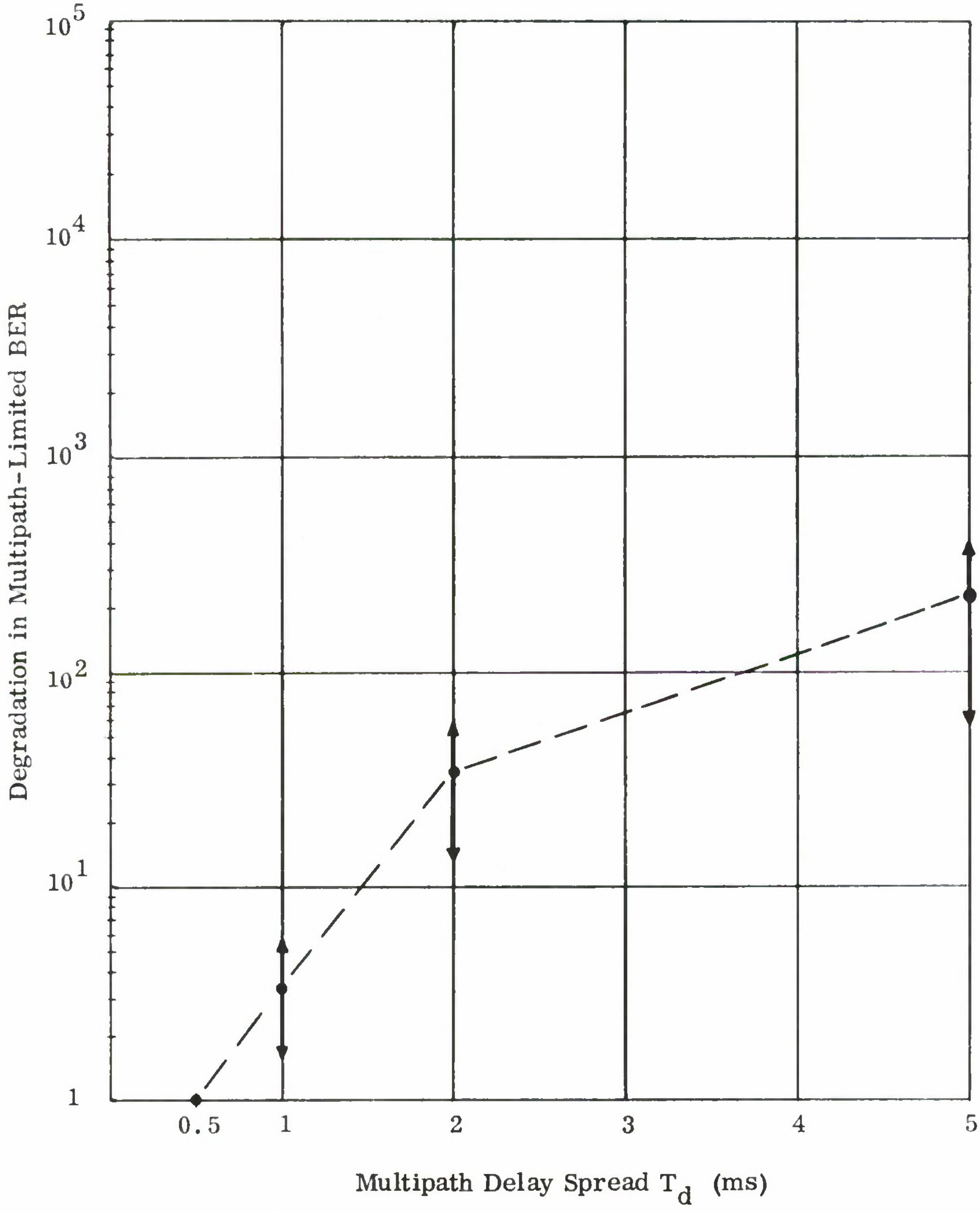
● Mean value for all fading bandwidths. All data normalized to 0.5 ms multipath delay spread.

Figure 26. Degradation in Multipath-Limited BER as a Function of Multipath Delay Spread, 2400 bps/4-phase, Nondiversity



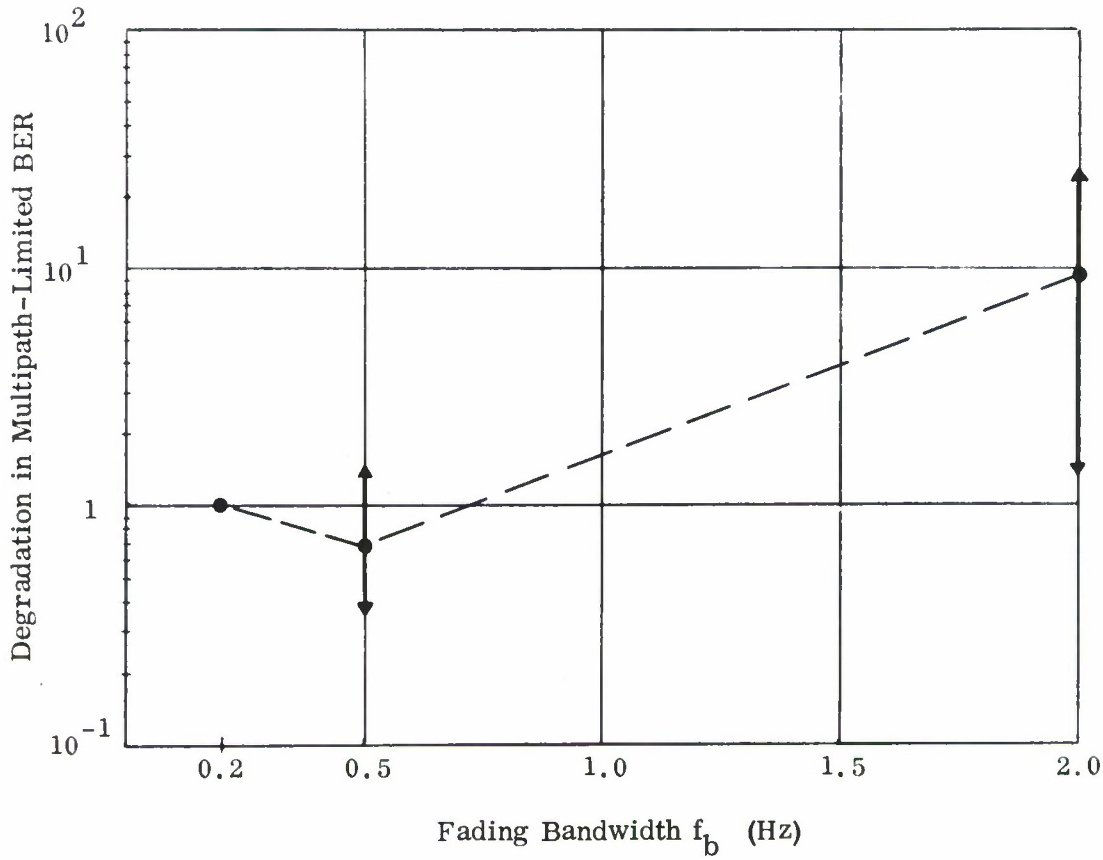
● Mean value for all fading bandwidths. All data normalized to 0.5 ms multipath delay spread.

Figure 27. Degradation in Multipath-Limited BER as a Function of Multipath Delay Spread, 2400 bps/2-phase, Diversity



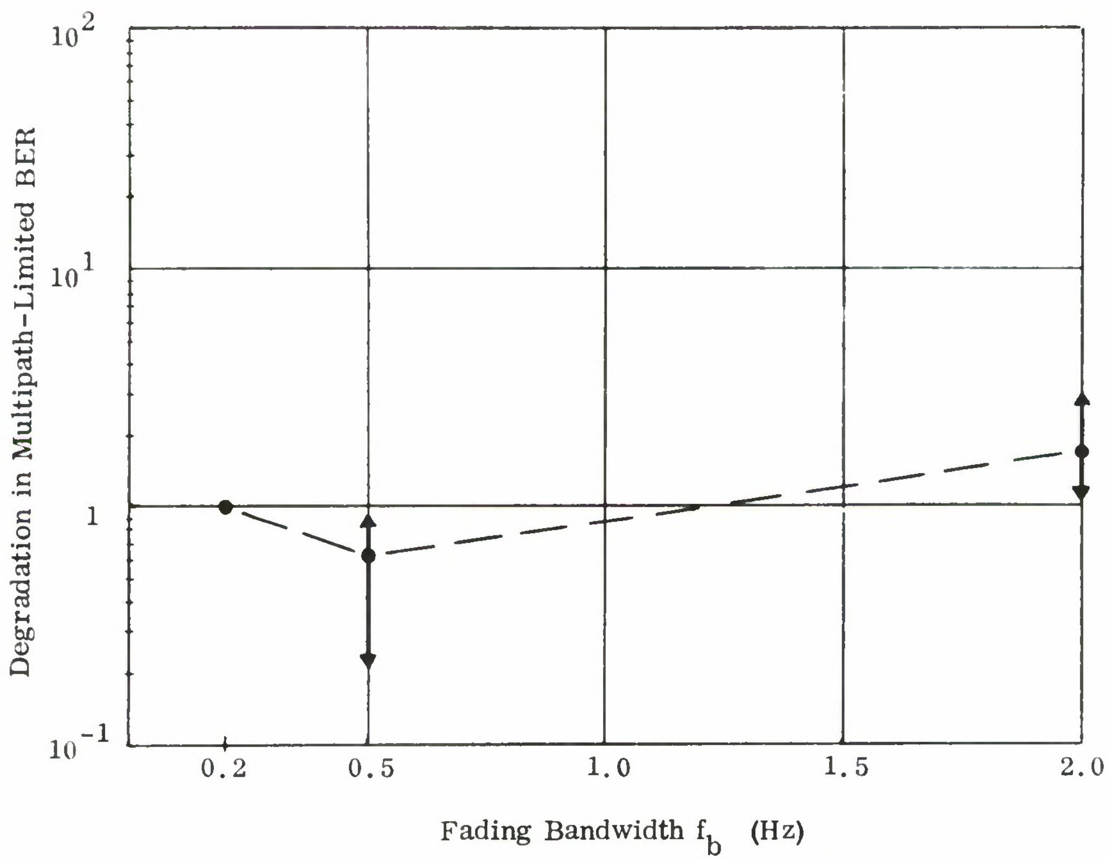
● Mean value for all fading bandwidths. All data normalized to 0.5 ms multipath delay spread.

Figure 28. Degradation in Multipath-Limited BER as a Function of Fading Bandwidth, 2400 bps/2-phase, Nondiversity



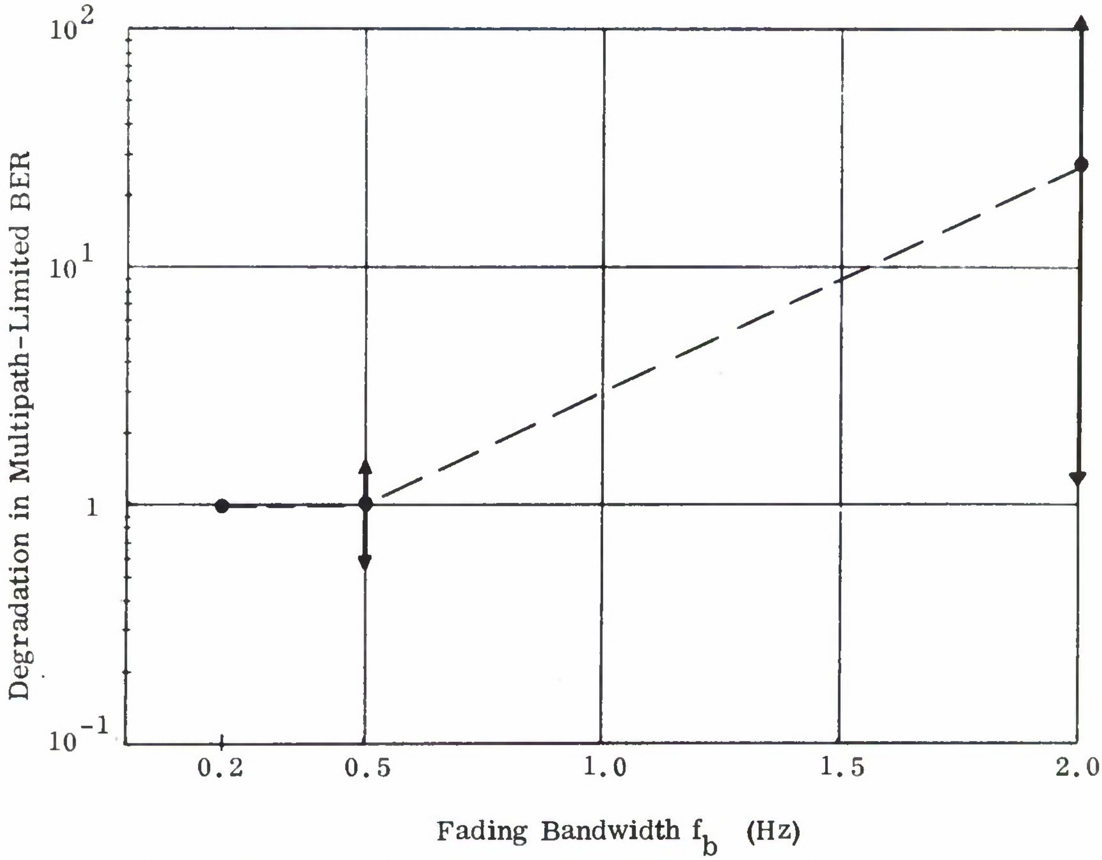
● Mean value for all multipath delay spreads. All data normalized to 0.2 Hz fading bandwidth.

Figure 29. Degradation in Multipath-Limited BER as a Function of Fading Bandwidth, 4800 bps, Diversity



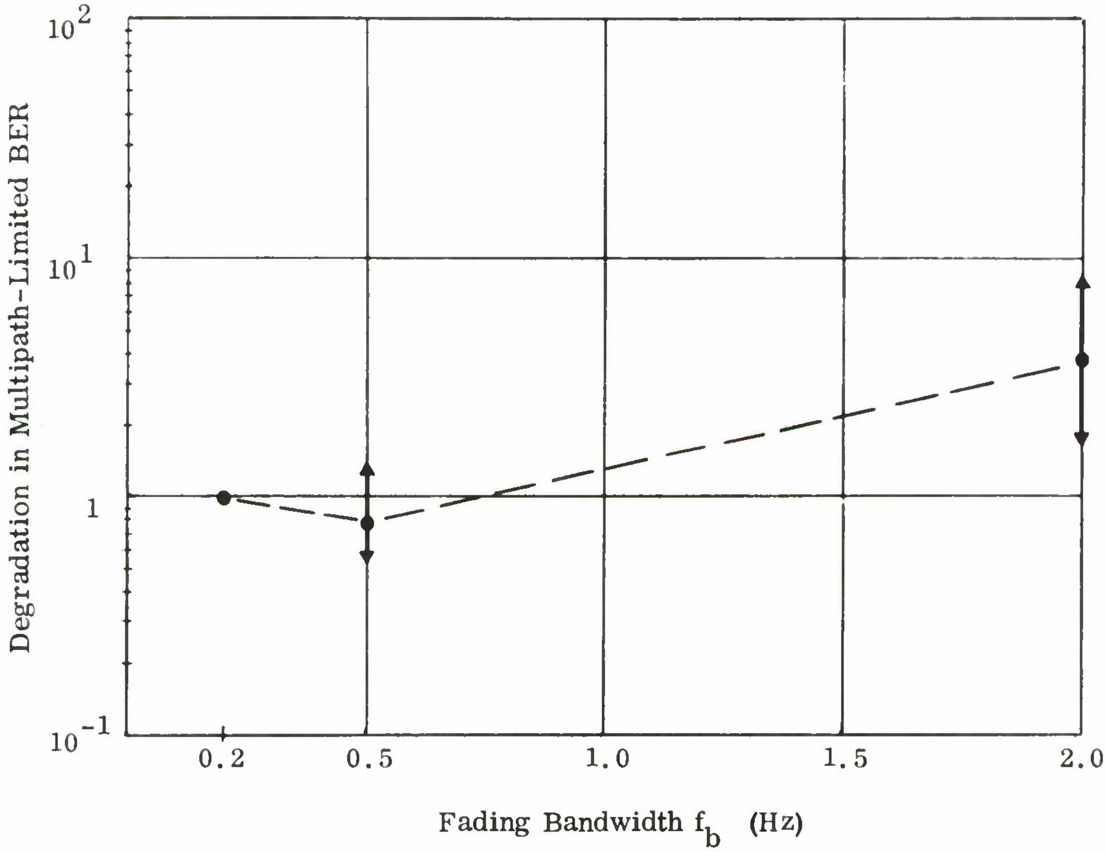
● Mean value for all multipath delay spreads. All data normalized to 0.2 Hz fading bandwidth.

Figure 30. Degradation in Multipath-Limited BER as a Function of Fading Bandwidth, 4800 bps, Nondiversity



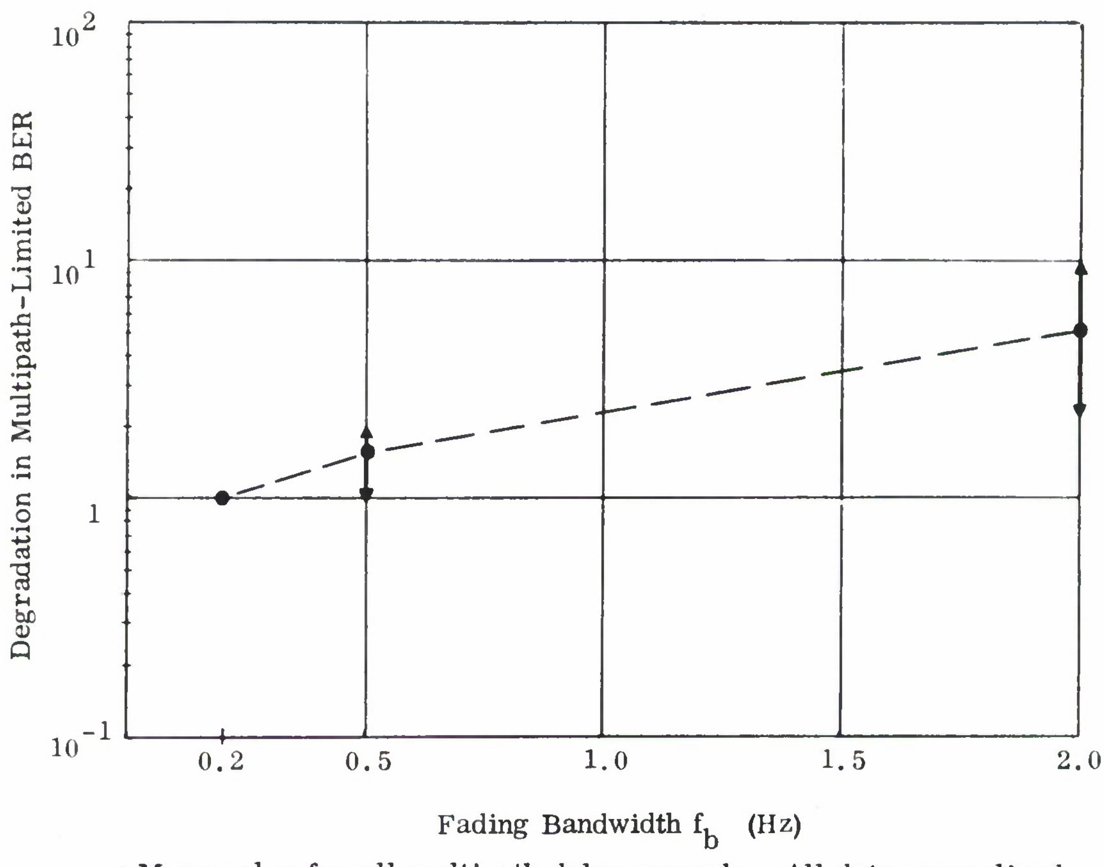
● Mean value for all multipath delay spreads. All data normalized to 0.2 Hz fading bandwidth.

Figure 31. Degradation in Multipath-Limited BER as a Function of Fading Bandwidth, 2400 bps/4-phase, Diversity



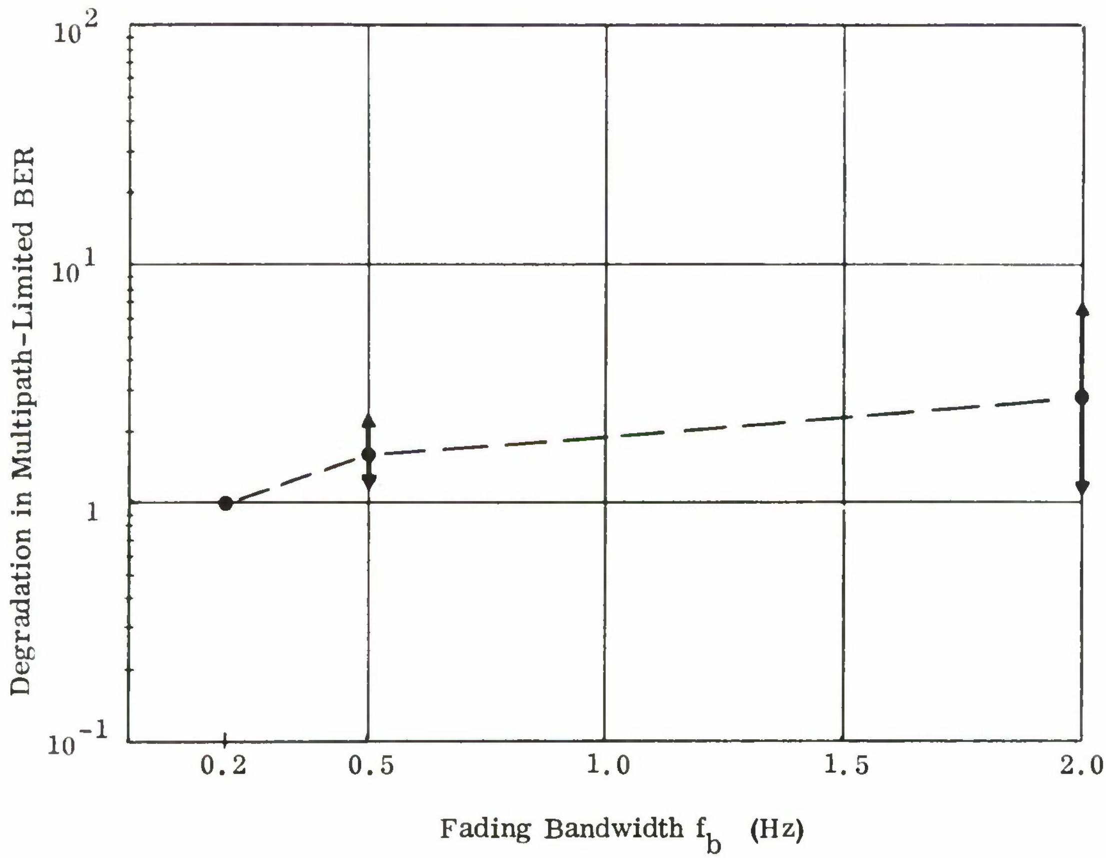
● Mean value for all multipath delay spreads. All data normalized to 0.2 Hz fading bandwidth.

Figure 32. Degradation in Multipath-Limited BER as a Function of Fading Bandwidth, 2400 bps/4-phase, Nondiversity



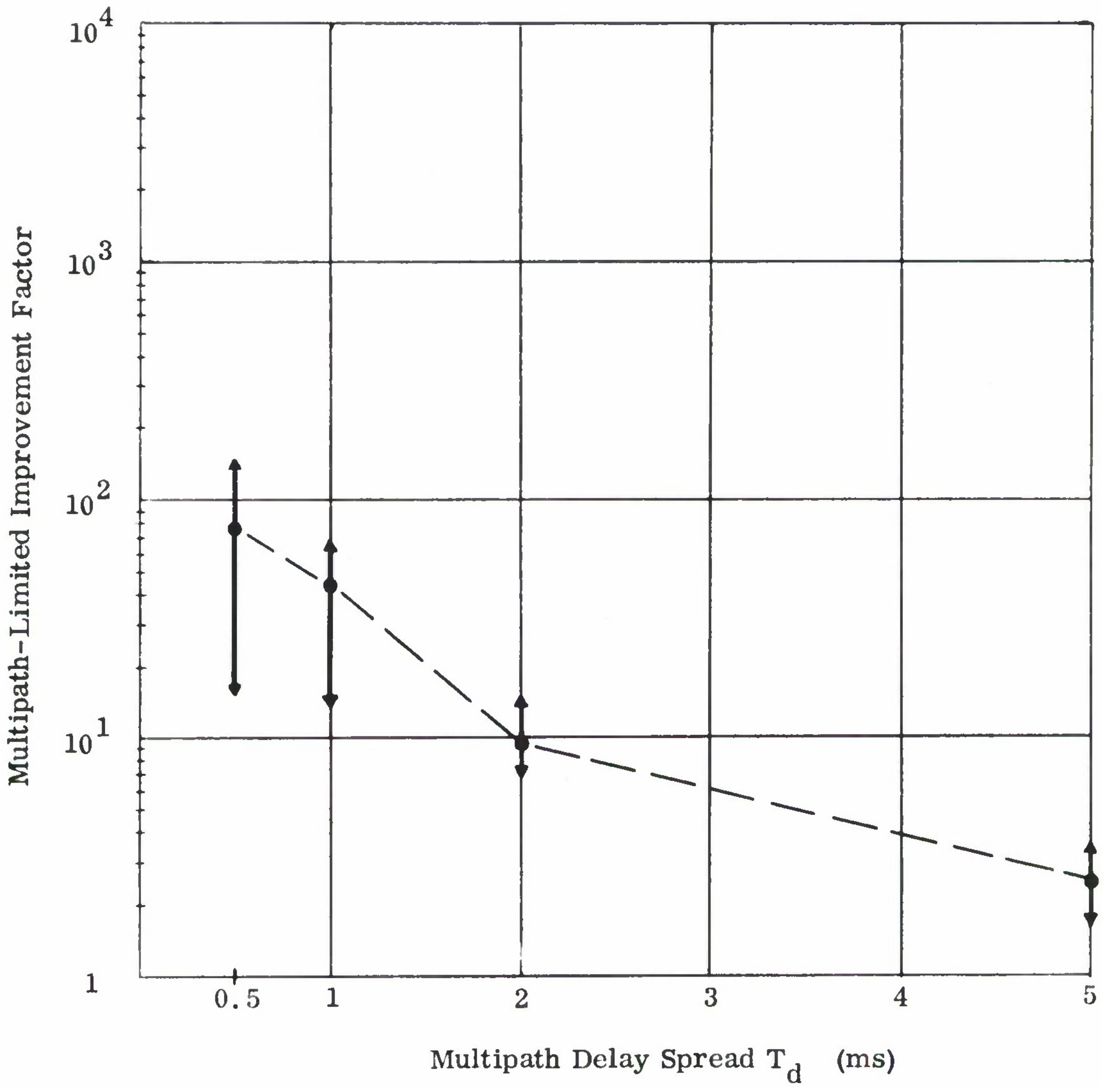
● Mean value for all multipath delay spreads. All data normalized to 0.2 Hz fading bandwidth.

Figure 33. Degradation in Multipath-Limited BER as a Function of Fading Bandwidth, 2400 bps/2-phase, Diversity



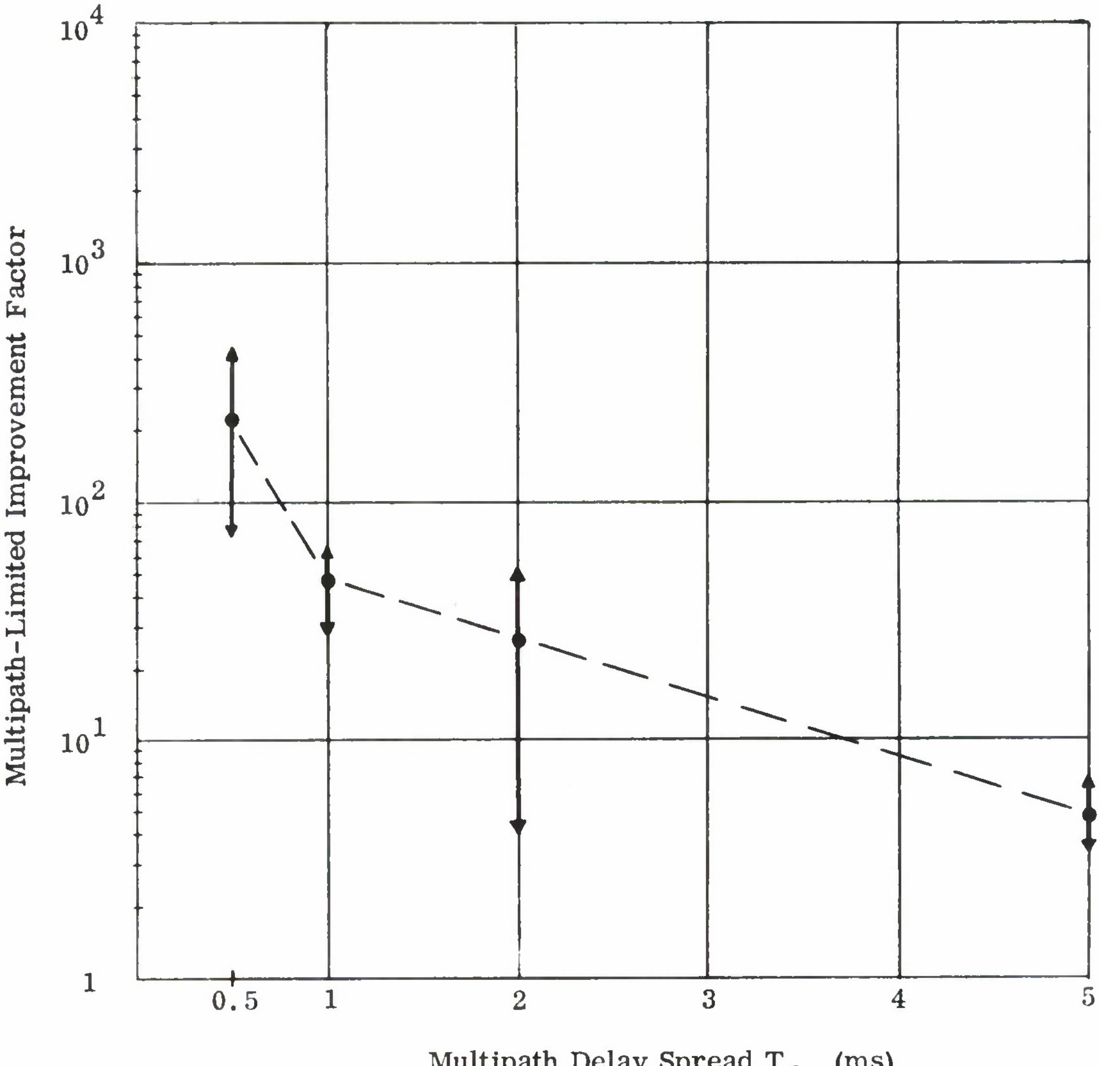
• Mean value for all multipath delay spreads. All data normalized to 0.2 Hz fading bandwidth.

Figure 34. Degradation in Multipath-Limited BER as a Function of Fading Bandwidth, 2400 bps/2-phase, Nondiversity



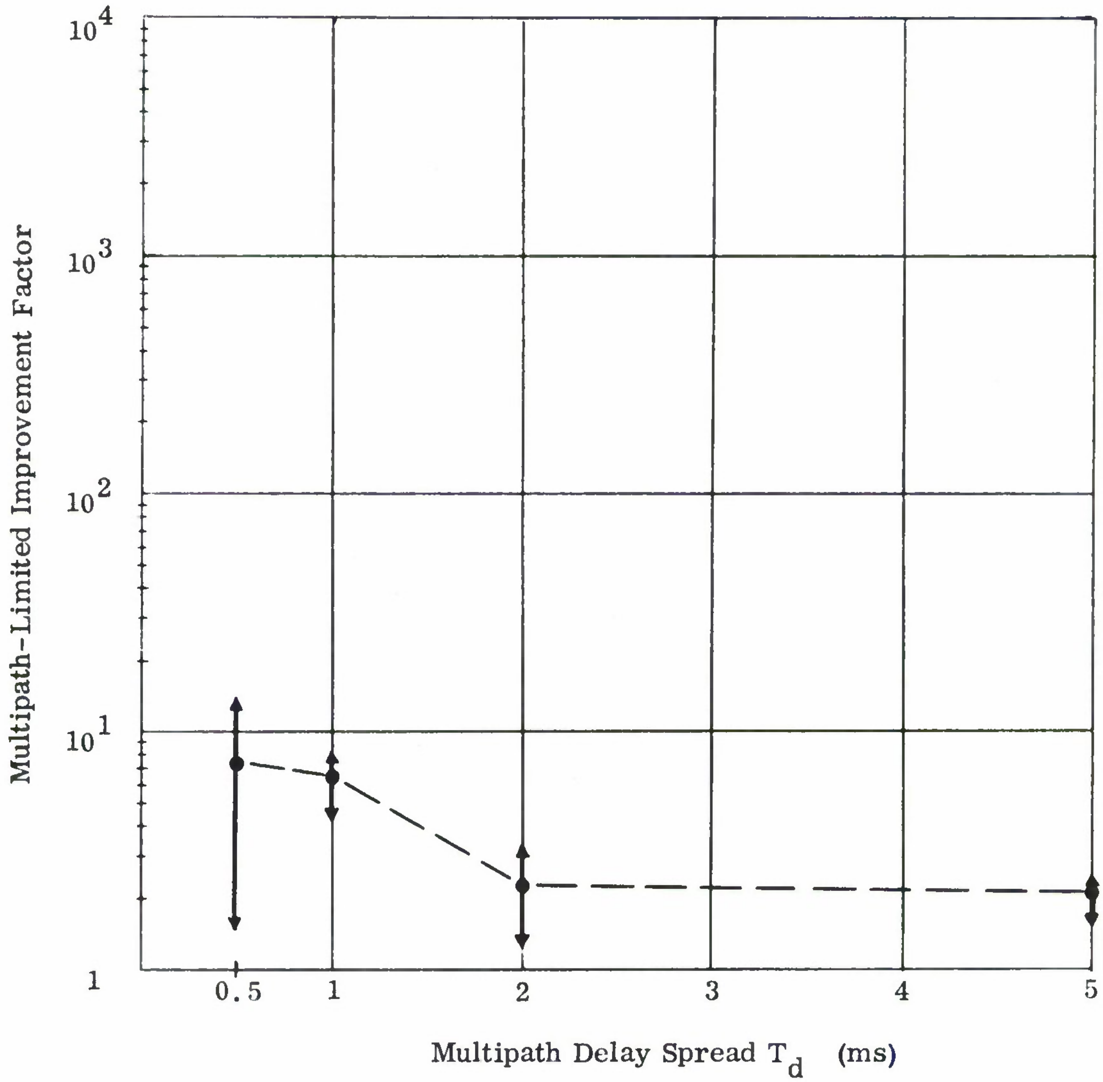
● Mean value for all fading bandwidths. See Section V Results for definition of factors A through G.

Figure 35. Multipath-Limited Improvement Factor (A)



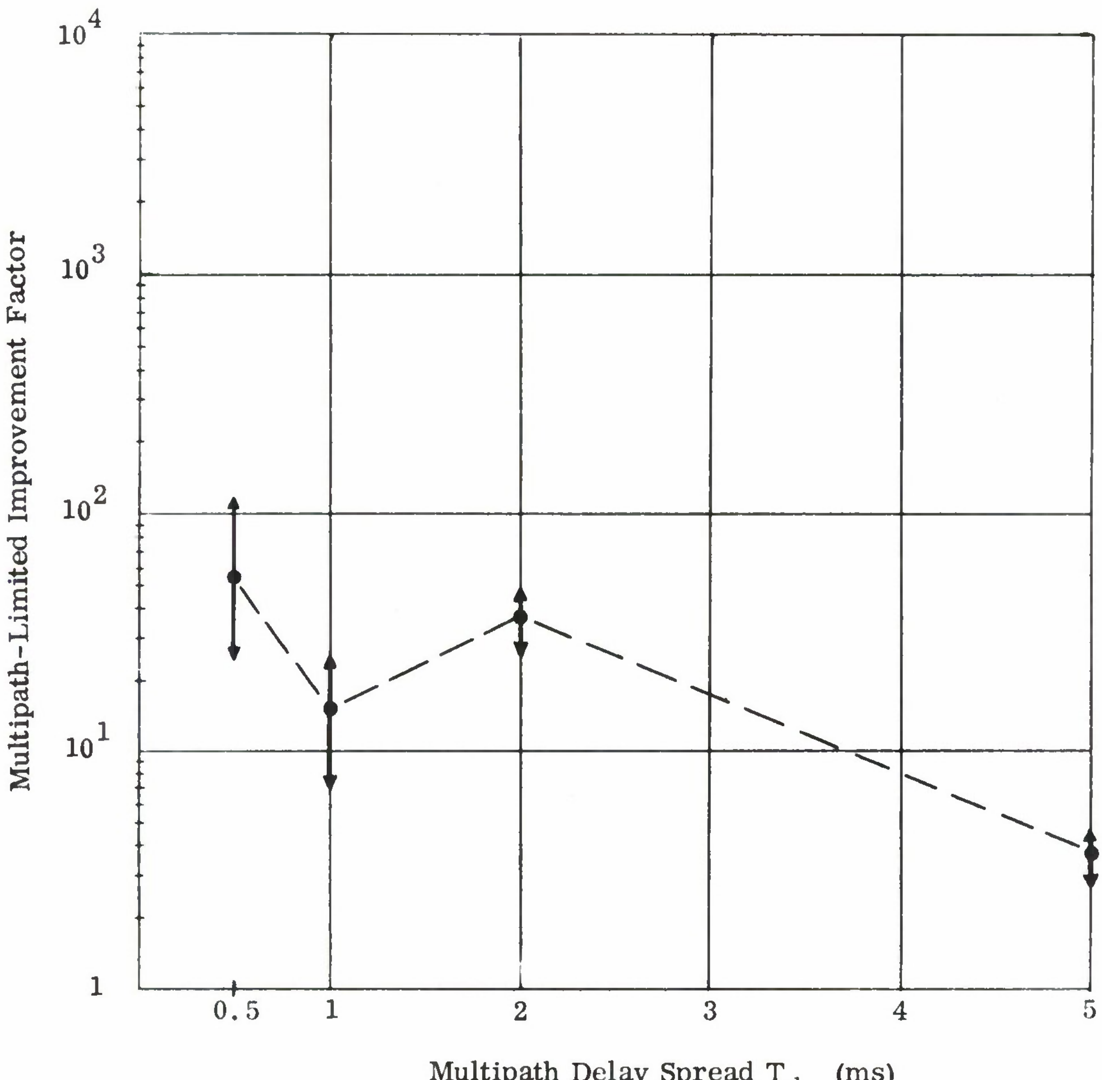
● Mean value for all fading bandwidths. See Section V Results for definition of factors A through G.

Figure 36. Multipath-Limited Improvement Factor (B)



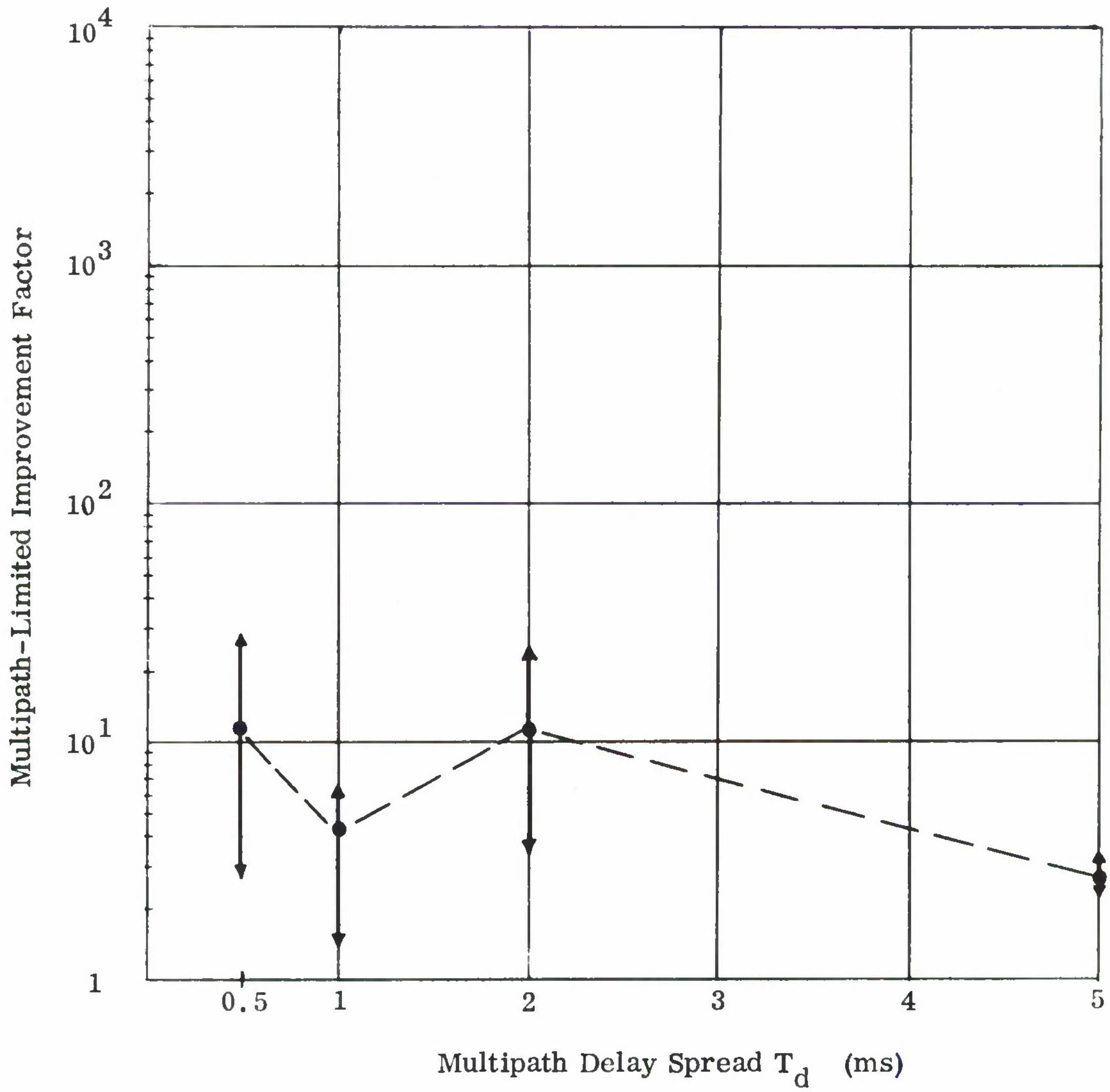
● Mean value for all fading bandwidths. See Section V Results for definition of factors A through G.

Figure 37. Multipath-Limited Improvement Factor (C)



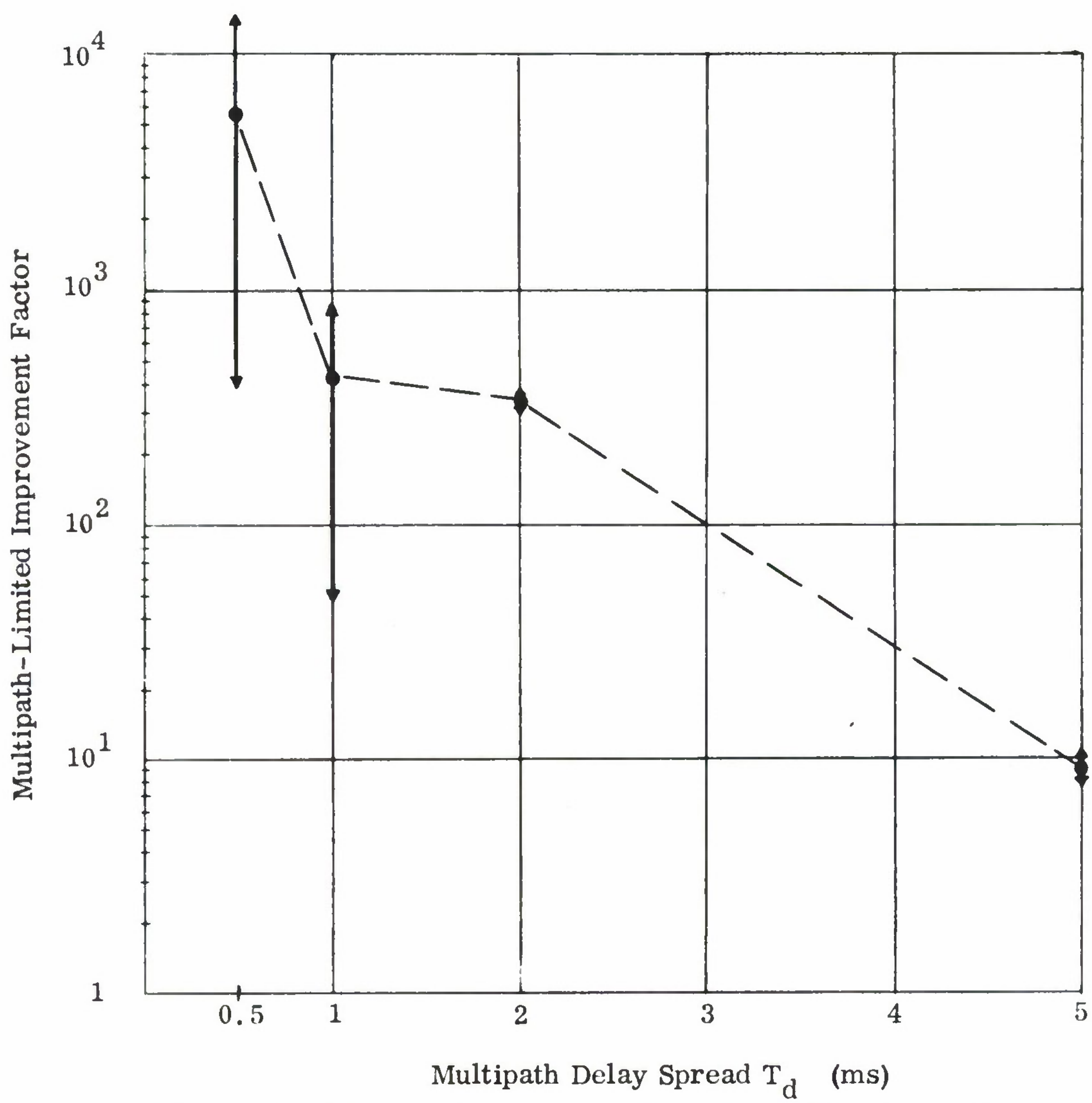
● Mean value for all fading bandwidths. See Section V Results for definition of factors A through G.

Figure 38. Multipath-Limited Improvement Factor (D)



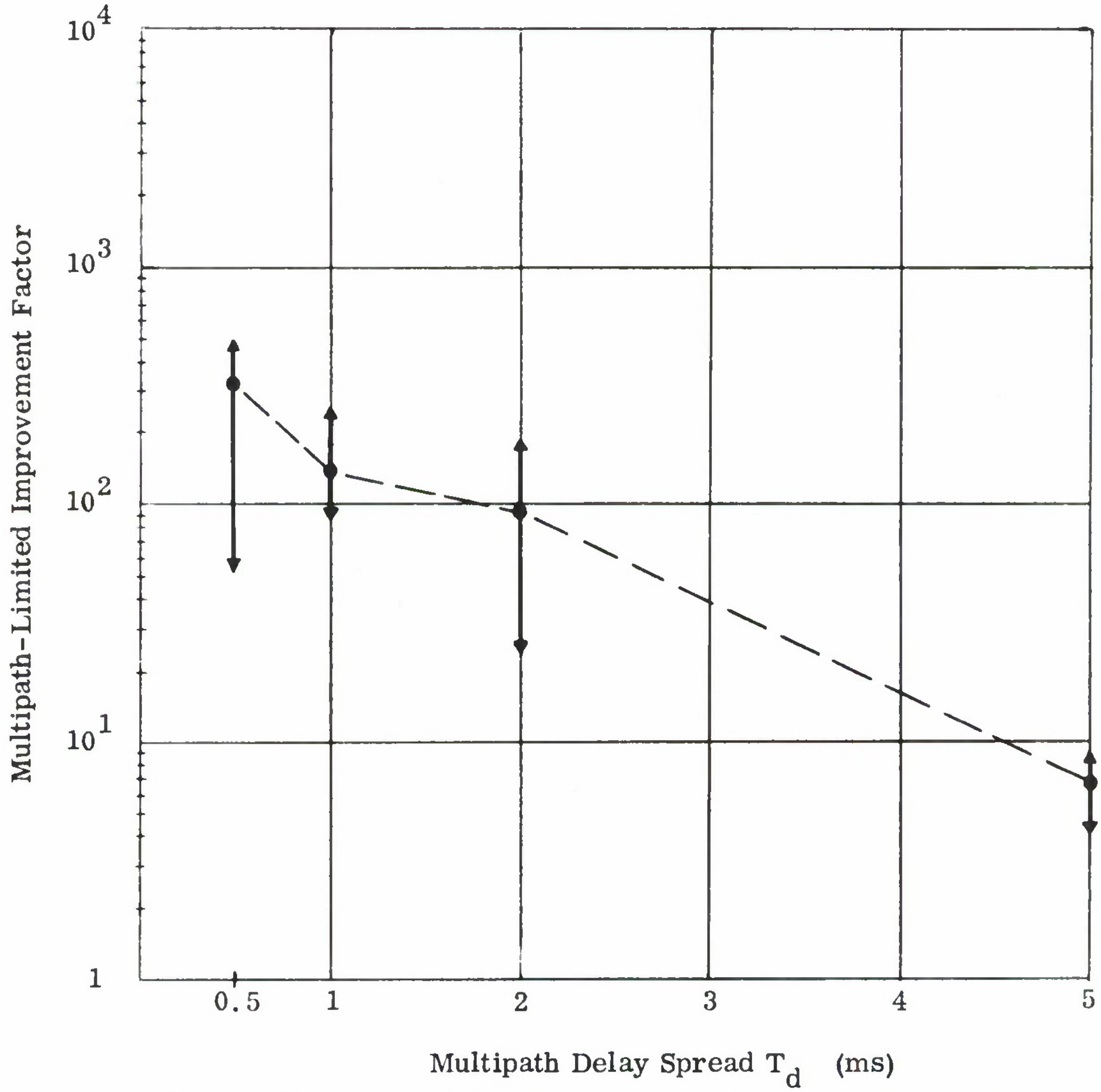
● Mean value for all fading bandwidths. See Section V Results for definition of factors A through G.

Figure 39. Multipath-Limited Improvement Factor (E)



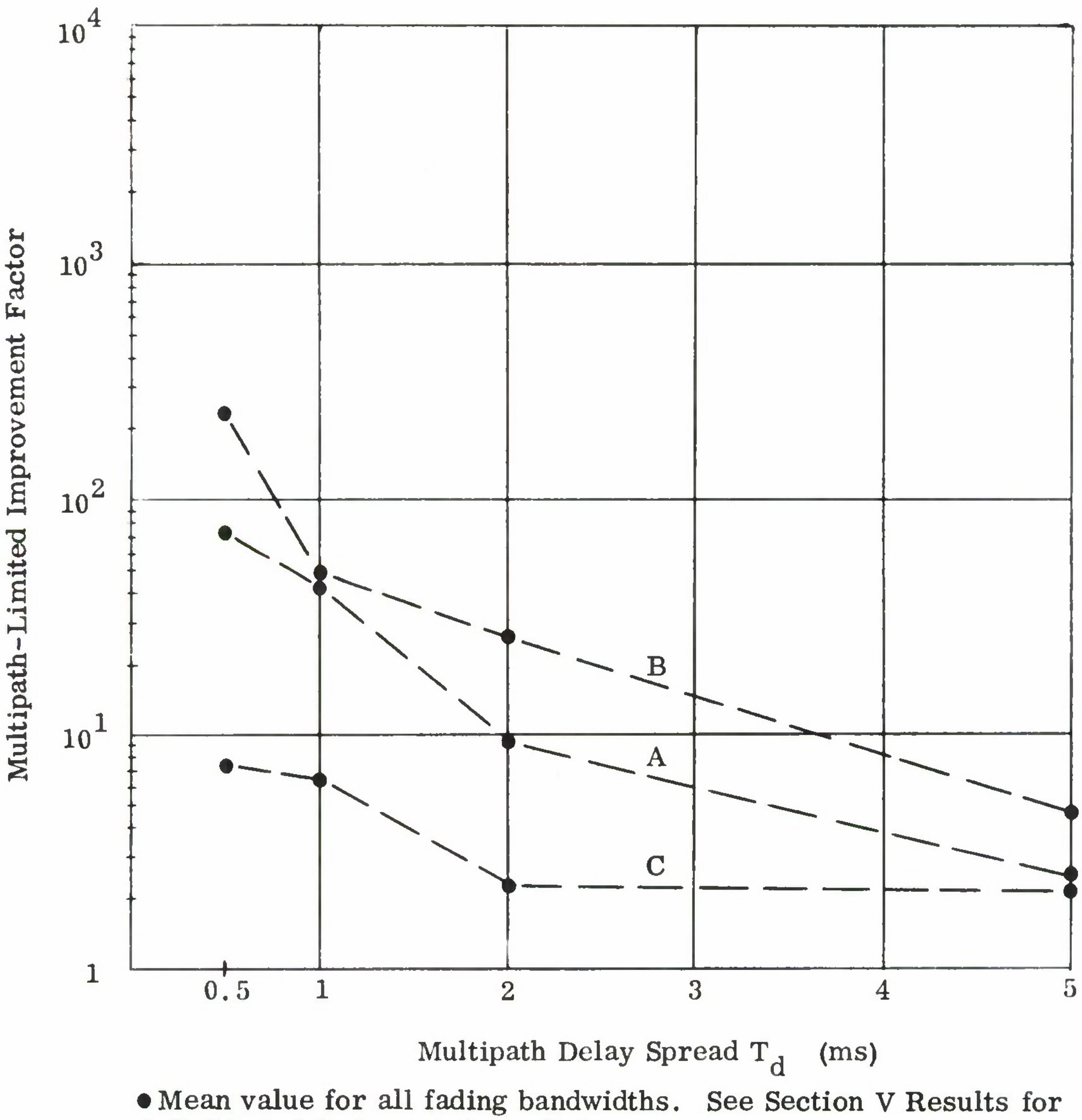
● Mean value for all fading bandwidths. See Section V Results for definition of factors A through G.

Figure 40. Multipath-Limited Improvement Factor (F)



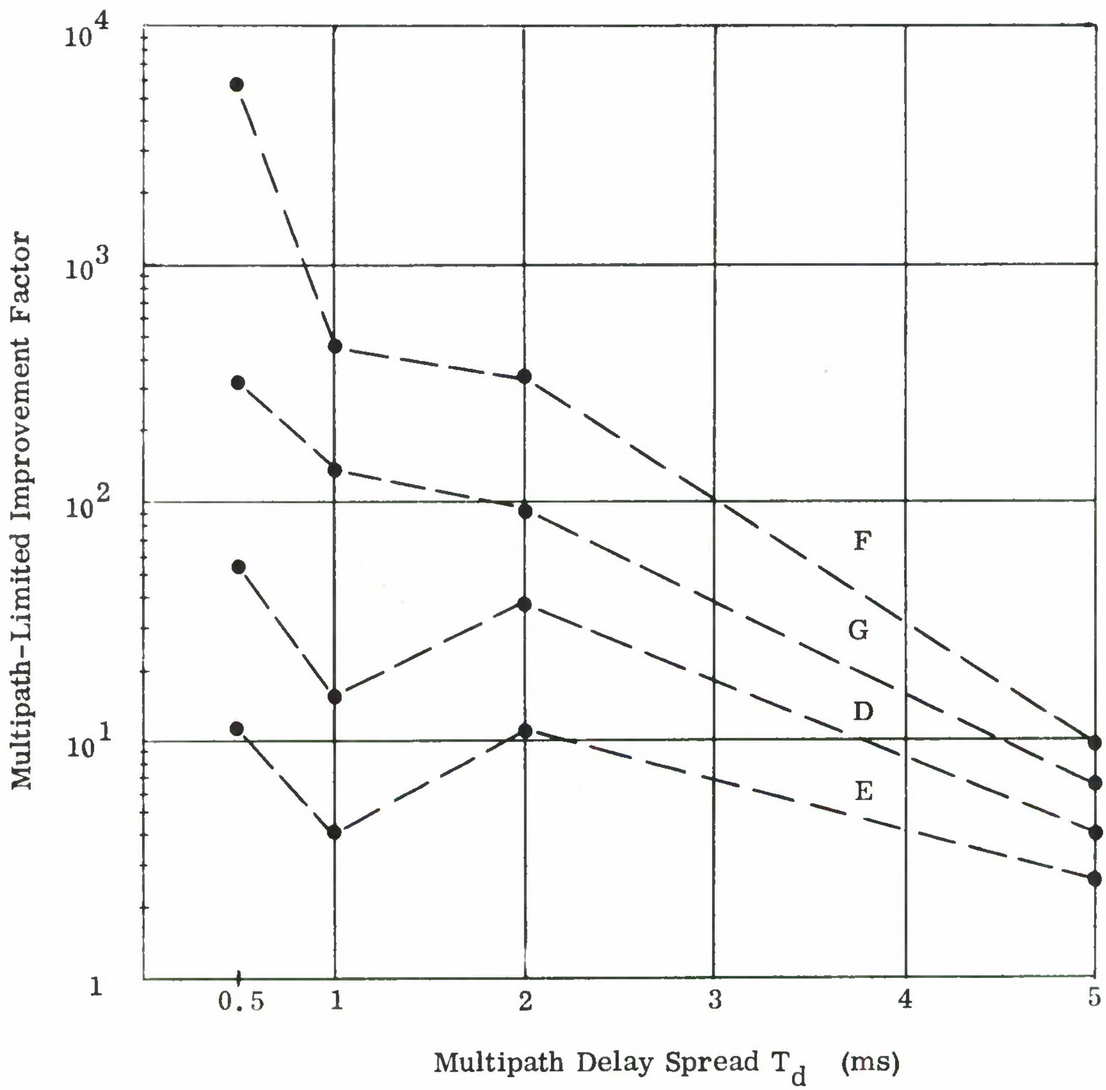
● Mean value for all fading bandwidths. See Section V Results for definition of factors A through G.

Figure 41. Multipath-Limited Improvement Factor (G)



● Mean value for all fading bandwidths. See Section V Results for definition of factors A through G.

Figure 42. Comparison: Multipath-Limited Improvement Factors A, B, and C



● Mean value for all fading bandwidths. See Section V Results for definition of factors A through G.

Figure 43. Comparison: Multipath-Limited Improvement Factors D, E, F, and G

SECTION VI

CONCLUSIONS

The following conclusions are based on the results of the laboratory test program as described.

1. The largest degradation in BER is caused by increasing multipath delay spread. Degradations in BER between one and two orders of magnitude were commonly observed over all modes of operation for multipath delay spreads in the order of 2 ms.

2. Increasing fading bandwidth produces a negligible effect on BER for fading bandwidths of 0.5 Hz. For a fading bandwidth of 2.0 Hz, the degradation seldom exceeds one order of magnitude.

3. Dual signal source diversity reception as implemented in the ANDEFT/SC-320 is an effective means for improving bit error rate. Improvement factors between one and two orders of magnitude were commonly observed for multipath delay spreads of 2 ms or less. Dual inband frequency diversity also proved to be an excellent technique for improving bit error rate. Results of testing this technique show slightly higher values of improvement factor when compared with reception diversity, especially for large values of multipath delay spread, i.e., 2 ms or larger. When the two means of diversity are combined, improvement factors of several orders of magnitude were observed for small multipath delay spreads.

4. The best mode of operation was the 2400 bps/4-phase mode which includes both dual signal source diversity reception and dual inband frequency diversity for 4-way diversity. For small fading bandwidths and multipath delay spreads, the multipath-limited BER in this mode was so low it could not be established for data samples as large as 10^7 bits.

5. Mode for mode, the 2400 bps/4-phase mode was superior in performance to the 2400 bps/2-phase mode. The success of this mode is due to the implementation of the dual inband frequency diversity which utilizes channels separated by 1320 Hz.

APPENDIX

DATA SHEET - 1

Data Run/Point Ident No.	Total Bits	Bit Errors	Bit Error Rate
1111	10,000,173	99,337	9.93×10^{-3}
1112	10,000,392	2,455	2.46×10^{-4}
1113	10,000,269	67	6.70×10^{-6}
1121	10,000,241	131,668	1.32×10^{-2}
1122	10,000,156	3,358	3.36×10^{-4}
1123	10,000,328	517	5.17×10^{-5}
1131	10,000,672	169,459	1.70×10^{-2}
1132	10,000,492	21,594	2.16×10^{-3}
1133	10,000,357	13,795	1.38×10^{-3}
1141	10,000,251	502,912	5.03×10^{-2}
1142	10,000,198	179,642	1.80×10^{-2}
1143	10,000,624	155,326	1.55×10^{-2}
1211	10,000,465	554,966	5.55×10^{-2}
1212	10,000,127	65,904	6.59×10^{-3}
1213	10,000,332	9,423	9.42×10^{-4}
1221	10,000,261	589,735	5.90×10^{-2}
1222	10,000,218	85,491	8.55×10^{-3}
1223	20,000,512	52,097	2.61×10^{-3}
1231	10,000,498	642,650	6.43×10^{-2}
1232	10,000,443	158,956	1.59×10^{-2}
1233	10,000,149	99,853	9.99×10^{-3}
1241	10,000,285	972,424	9.72×10^{-2}
1242	10,000,290	596,510	5.97×10^{-2}
1243	10,000,227	545,803	5.46×10^{-2}

APPENDIX

DATA SHEET - 2

Data Run/Point Ident No.	Total Bits	Bit Errors	Bit Error Rate
1311	5,000,163	36,642	7.33×10^{-3}
1312	5,000,165	254	5.08×10^{-5}
1313	15,000,269	0	$< 6.60 \times 10^{-8}$
1321	5,000,219	44,093	8.82×10^{-3}
1322	5,000,088	419	8.38×10^{-5}
1323	20,000,492	60	3.00×10^{-6}
1331	5,000,274	47,442	9.49×10^{-3}
1332	5,000,055	736	1.47×10^{-4}
1333	5,000,519	159	3.18×10^{-5}
1341	5,000,436	132,709	2.65×10^{-2}
1342	5,000,456	37,240	7.45×10^{-3}
1343	5,000,576	27,512	5.50×10^{-3}
1411	5,000,123	272,377	5.45×10^{-2}
1412	5,000,175	14,222	2.84×10^{-3}
1413	40,000,139	90	2.25×10^{-6}
1421	5,000,017	273,939	5.48×10^{-2}
1422	12,000,144	32,471	2.71×10^{-3}
1423	5,000,078	277	5.54×10^{-5}
1431	5,000,137	241,635	4.83×10^{-2}
1432	5,000,122	13,397	2.68×10^{-3}
1433	5,000,122	2,127	4.25×10^{-4}
1441	5,000,459	270,929	5.42×10^{-2}
1442	5,000,172	48,983	9.80×10^{-3}
1443	10,000,116	81,832	8.18×10^{-3}

APPENDIX

DATA SHEET - 3

Data Run/Point Ident No.	Total Bits	Bit Errors	Bit Error Rate
1511	5,000,029	14,633	2.93×10^{-3}
1512	5,000,130	168	3.36×10^{-5}
1513	5,000,050	12	2.40×10^{-6}
1521	5,000,018	19,087	3.82×10^{-3}
1522	5,000,229	352	7.52×10^{-5}
1523	5,000,132	54	1.08×10^{-5}
1531	5,000,162	31,314	6.26×10^{-3}
1532	5,000,012	869	1.74×10^{-4}
1533	5,000,021	276	5.52×10^{-5}
1541	5,000,276	119,482	2.39×10^{-2}
1542	5,000,088	42,201	8.44×10^{-3}
1543	5,000,042	33,296	6.66×10^{-3}
1611	5,000,067	140,357	2.81×10^{-2}
1612	5,000,598	8,646	1.73×10^{-3}
1613	5,000,078	318	6.36×10^{-5}
1621	5,000,062	168,317	3.37×10^{-2}
1622	5,000,116	16,366	3.27×10^{-3}
1623	5,000,215	1,612	3.22×10^{-4}
1631	5,000,551	162,287	3.25×10^{-2}
1632	5,000,077	36,704	7.34×10^{-3}
1633	5,000,073	16,465	3.29×10^{-3}
1641	5,000,057	274,722	5.49×10^{-2}
1642	5,000,170	131,100	2.62×10^{-2}
1643	5,000,236	114,594	2.29×10^{-2}

APPENDIX

DATA SHEET - 4

Data Run/Point Ident No.	Total Bits	Bit Errors	Bit Error Rate
2111	5,000,602	19,978	4.00×10^{-3}
2112	5,000,196	235	4.70×10^{-5}
2113	25,000,335	86	3.44×10^{-6}
2121	5,000,180	21,045	4.21×10^{-3}
2122	5,000,054	598	1.20×10^{-4}
2123	5,000,074	144	2.88×10^{-5}
2131	5,000,085	40,540	8.11×10^{-3}
2132	5,000,232	5,827	1.17×10^{-3}
2133	5,000,241	2,489	4.98×10^{-4}
2141	5,000,029	170,787	3.16×10^{-2}
2142	5,000,090	105,415	2.11×10^{-2}
2143	5,000,297	105,226	2.10×10^{-2}
2211	5,000,018	152,208	3.04×10^{-2}
2212	5,000,036	8,789	1.66×10^{-3}
2213	20,000,460	4,210	2.11×10^{-4}
2221	5,000,135	165,662	3.31×10^{-2}
2222	5,000,175	20,514	4.10×10^{-3}
2223	5,000,144	9,186	1.84×10^{-3}
2231	5,000,001	190,821	2.87×10^{-2}
2232	5,000,247	47,201	9.44×10^{-3}
2233	5,000,511	33,793	6.76×10^{-3}
2241	5,000,306	447,601	8.95×10^{-2}
2242	5,000,177	267,321	5.35×10^{-2}
2243	5,000,535	237,182	4.74×10^{-2}

APPENDIX

DATA SHEET - 5

Data Run/Point Ident No.	Total Bits	Bit Errors	Bit Error Rate
2311	2,500,137	12,589	5.07×10^{-3}
2312	2,500,137	34	1.36×10^{-5}
2313	10,000,168	0	$< 1.00 \times 10^{-7}$
2321	2,500,221	13,126	5.25×10^{-3}
2322	2,500,112	126	5.04×10^{-5}
2323	5,000,156	20	4.00×10^{-6}
2331	2,500,081	18,114	7.25×10^{-3}
2332	2,500,088	267	1.07×10^{-4}
2333	2,500,050	45	1.80×10^{-5}
2341	2,500,236	50,291	2.01×10^{-2}
2342	2,500,187	14,151	5.66×10^{-3}
2343	2,500,108	11,420	4.57×10^{-3}
2411	2,500,085	99,193	3.97×10^{-2}
2412	2,500,213	2,722	1.09×10^{-3}
2413	5,000,101	6	1.20×10^{-6}
2421	2,500,176	93,909	3.76×10^{-2}
2422	2,500,125	3,255	1.30×10^{-3}
2423	2,500,065	73	2.92×10^{-5}
2431	2,500,002	78,374	3.14×10^{-2}
2432	2,500,102	3,207	1.28×10^{-3}
2433	2,500,183	327	1.31×10^{-4}
2441	2,500,203	101,161	4.05×10^{-2}
2442	2,500,100	31,082	1.24×10^{-2}
2443	2,500,120	27,042	1.08×10^{-2}

APPENDIX

DATA SHEET - 6

Data Run/Point Ident No.	Total Bits	Bit Errors	Bit Error Rate
2511	2,499,980	9,617	3.85×10^{-3}
2512	2,500,182	107	4.28×10^{-5}
2513	15,000,221	59	3.93×10^{-6}
2521	2,500,116	16,987	6.80×10^{-3}
2522	2,500,186	246	9.84×10^{-5}
2523	2,500,160	52	2.08×10^{-5}
2531	2,500,239	14,103	5.64×10^{-3}
2532	2,500,052	725	2.90×10^{-4}
2533	2,500,032	254	1.02×10^{-4}
2541	2,500,220	49,359	1.97×10^{-2}
2542	2,500,109	20,336	8.13×10^{-3}
2543	2,500,190	16,519	6.61×10^{-3}
2611	2,500,074	75,135	2.31×10^{-2}
2612	2,500,174	4,406	1.76×10^{-3}
2613	2,500,235	378	1.51×10^{-4}
2621	2,500,069	102,272	4.09×10^{-2}
2622	2,500,051	8,376	3.35×10^{-3}
2623	2,500,358	1,149	4.60×10^{-4}
2631	2,500,190	165,700	6.63×10^{-2}
2632	2,500,174	31,497	1.26×10^{-2}
2633	2,500,058	14,919	5.97×10^{-3}
2641	2,500,230	181,563	7.26×10^{-2}
2642	2,500,087	83,095	3.24×10^{-2}
2643	2,500,207	71,412	2.86×10^{-2}

APPENDIX

DATA SHEET - 7

Data Run/Point Ident No.	Total Bits	Bit Errors	Bit Error Rate
3111	2,000,442	20,716	1.04×10^{-2}
3112	2,000,357	871	4.36×10^{-4}
3113	2,000,323	356	1.78×10^{-4}
3121	2,000,188	32,606	1.63×10^{-2}
3122	2,000,000	2,251	1.13×10^{-3}
3123	15,000,056	5,406	3.60×10^{-4}
3131	2,000,008	36,685	1.83×10^{-2}
3132	2,000,348	5,788	2.89×10^{-3}
3133	2,000,125	3,774	1.89×10^{-3}
3141	2,000,212	115,682	5.78×10^{-2}
3142	2,000,024	71,895	3.60×10^{-2}
3143	2,000,007	68,121	3.41×10^{-2}
3211	2,000,057	105,870	5.29×10^{-2}
3212	2,000,024	16,029	8.02×10^{-3}
3213	2,000,268	5,540	2.77×10^{-3}
3221	2,000,090	128,655	6.43×10^{-2}
3222	2,000,027	23,670	1.18×10^{-2}
3223	2,000,477	10,142	5.07×10^{-3}
3231	1,999,999	143,271	7.16×10^{-2}
3232	2,000,166	41,446	2.07×10^{-2}
3233	2,000,150	27,200	1.36×10^{-2}
3241	2,000,079	205,786	1.03×10^{-1}
3242	2,000,231	129,432	6.47×10^{-2}
3243	2,000,689	120,435	6.02×10^{-2}

APPENDIX

DATA SHEET - 8

Data Run/Point Ident No.	Total Bits	Bit Errors	Bit Error Rate
3311	1,000,133	6,773	6.77×10^{-3}
3312	1,000,043	84	8.40×10^{-5}
3313	6,000,335	42	7.00×10^{-6}
3321	1,000,051	8,643	8.64×10^{-3}
3322	1,000,148	77	7.70×10^{-5}
3323	3,000,006	43	1.43×10^{-5}
3331	1,000,086	9,438	9.44×10^{-3}
3332	1,000,103	180	1.80×10^{-4}
3333	1,000,180	43	4.30×10^{-5}
3341	1,000,103	32,307	3.23×10^{-2}
3342	1,000,047	9,644	9.64×10^{-3}
3343	1,000,156	7,815	7.82×10^{-3}
3411	1,000,121	42,777	4.28×10^{-2}
3412	1,000,002	1,877	1.88×10^{-3}
3413	1,000,012	40	4.00×10^{-5}
3421	1,000,177	50,173	5.02×10^{-2}
3422	1,000,168	2,549	2.55×10^{-3}
3423	1,000,316	180	$1,80 \times 10^{-4}$
3431	1,000,371	54,932	5.49×10^{-2}
3432	1,000,115	4,017	4.02×10^{-3}
3433	1,000,443	3,427	3.43×10^{-3}
3441	1,000,037	69,653	6.97×10^{-2}
3442	1,000,093	23,059	2.31×10^{-2}
3443	1,000,084	18,596	1.86×10^{-2}

APPENDIX

DATA SHEET - 9

Data Run/Point Ident No.	Total Bits	Bit Errors	Bit Error Rate
3511	1,000,046	1,333	1.33×10^{-3}
3512	1,000,187	21	2.10×10^{-5}
3513	1,000,131	6	6.00×10^{-6}
3521	1,000,293	3,147	3.15×10^{-3}
3522	1,000,016	180	1.80×10^{-4}
3523	1,000,007	59	5.90×10^{-5}
3531	1,000,051	5,216	5.22×10^{-3}
3532	1,000,331	762	7.62×10^{-4}
3533	1,000,023	540	5.40×10^{-4}
3541	1,000,174	25,458	2.55×10^{-2}
3542	1,000,236	15,386	1.54×10^{-2}
3543	1,000,225	14,717	1.47×10^{-2}
3611	1,000,157	10,948	1.10×10^{-2}
3612	1,000,140	1,030	1.03×10^{-3}
3613	1,000,191	420	4.20×10^{-4}
3621	1,000,115	14,436	1.44×10^{-2}
3622	1,000,388	1,761	1.76×10^{-3}
3623	1,000,200	711	7.11×10^{-4}
3631	1,000,352	38,645	3.87×10^{-2}
3632	1,000,054	8,578	8.58×10^{-3}
3633	1,000,328	5,623	5.62×10^{-3}
3641	1,000,068	57,280	5.73×10^{-2}
3642	1,000,430	30,518	3.05×10^{-2}
3643	1,000,047	27,409	2.74×10^{-2}

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13. ABSTRACT

A laboratory test program to evaluate the performance of the ANDEFT/SC-320 frequency-differential PSK HF modem operating with the General Dynamics HF Multipath Fading Channel Simulator is described. The modem was operated in six modes (4800 bps, 2400 bps/4-phase, and 2400 bps/2-phase; diversity and nondiversity) and performance was measured for simulated HF path conditions for four multipath delay spreads (0.5, 1, 2, and 5 ms), three fading bandwidths (0.2, 0.5, and 2.0 Hz), and three bit-energy-to-noise-density ratios (10, 20, and 40 db). The resulting data shows bit error rate performance at 4800 bps with diversity between 10^{-5} and 10^{-3} for multipath delay spreads between 0.5 and 2.0 ms, respectively, and a fading bandwidth of 0.2 Hz. Increasing multipath delay spread causes a much larger degradation in bit error rate than increasing fading bandwidth. Dual signal source reception diversity and dual inband frequency diversity are effective in producing improved bit error rates, especially at the smaller multipath delay spreads, i.e., 2 ms or less. Operation at 2400 bps/4-phase which includes both diversity techniques for 4-way diversity produced the best results. The multipath-limited error rate was so low for some channel parameters that it could not be established in 10^7 bits. For multipath-limited conditions, this mode out performed the 2400 bps/2-phase mode which does not include the inband diversity feature.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Radio Communication Systems (HF)						
Ionospheric Transmission						